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SYSTEM) EVALUATION (U) FEDERAL AVIATION ADMINISTRATION
TECHNICAL CENTER ATLANTIC CIT. A J REHMANN JUL 86
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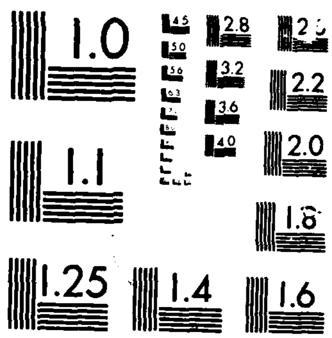
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Rotorcraft TCAS Evaluation Group 2 Results

Albert J. Rehmann

July 1986

DOT/FAA/CT-TN86/24

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16. Abstract

The results of antenna and surveillance testing are described in this report. Two Traffic Alert and Collision Avoidance System (TCAS) antenna sites were chosen for the Sikorsky S-76, and both proved suitable for a single antenna installation. The particular effects of helicopter operation on existing TCAS surveillance were examined. Recommended changes will be tested following Group 3 flight tests.

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EXECUTIVE SUMMARY

This report contains the results of Group 2 testing of a Traffic Alert and Collision Avoidance System (TCAS) installation in a Sikorsky S-76. Of the three groups in the S-76 TCAS evaluation effort, Group 2 was the most substantive because the important work of specifying the characteristics of the antenna installation and the particular effects of multipath were both accomplished. Transmitter and receiver specifications were also developed. Two antenna sites, one atop the nose and one on the underside of the tail boom, were evaluated. Each site is a suitable location for a single antenna TCAS. By comparison, the bottom antenna has better bearing performance and slightly better coverage, while the top antenna is far less corrupted by multipath. The relative merits of each antenna will be further evaluated in Group 3 data analysis.

Through the examination of flight data, a three-step multipath elimination algorithm was developed. It will be implemented and evaluated as part of Group 3 flight data reduction.

Minimum transmit power and receiver sensitivities were specified, based on a 90 percent probability of reply and a target range of 4 miles forward and 2.8 miles rearward. Effects of general aviation transponder characteristics and TCAS antenna patterns were also considered.

INTRODUCTION

BACKGROUND.

This report contains results from the second group of tests of a Traffic Alert and Collision Avoidance System (TCAS) Experimental Unit (TEU) installed in a Sikorsky S-76 helicopter.

A test plan (reference 1) was developed by ACT-140 which defined three major groups of tests. The end objectives of the tests were: (1) specify surveillance techniques pertaining to helicopter operations, and (2) examine radio frequency (RF) characteristics of directional antennas mounted on the top and bottom of the S-76 fuselage.

Earlier project activity included bench testing and Group 1 ramp and flight testing. This previous work was designed to verify the stand-alone TEU operation, and to validate system operation with the TEU installed in the S-76. The work was completed with all but two objectives attained. They were the compass swing (reference 1, pp 4.3.1) and antenna pattern measurement (reference 1, pp 4.3.2). These tests were repeated during group 2 testing.

The specific objectives of Group 2 tests were to partially satisfy end objective "1" by flight testing planned scenarios, which represent various phases of commercial helicopter operations with one or more Technical Center aircraft. End objective "2" was to be completely satisifed by Group 2 tests. To these, a third objective was added: complete the outstanding requirements of Group 1 and bench tests.

The scope of Group 2 test and data analysis was limited to data collection and analysis which satisfied the test plan objectives. Formal specification of surveillance techniques will be done after Group 3 testing.

TEST OVERVIEW.

Table 1 contains a brief review of progress and highlights some key dates.

Table 1, item 7, antenna coverage test was not completed. Due to electrical power limits in the helicopter the planned method of using a video recorder to store antenna pattern data was not executed. When video recording was determined to be unfeasible, ACT-140 engineers determined a scheme where the antenna patterns could be determined inferentially. This scheme is described in the discussion under "Test Conduct" for antenna coverage test.

TABLE 1. GROUP 2 ACCOMPLISHMENTS VS OBJECTIVES

Test Plan Reference	Test Description	Date Completed
N/A	TEU Installation in S-76	9/23-24/85
4.3.1	Compass Swing. Repeated from Group 2 tests	9/25/85
4.3.2	Static Antenna Pattern and Static AOA	9/25/85
4.4.7.1	Operational Flight Test-System Validation, Philadelphia Area	9/26/85
4.4.6	Encounters - Midair Conflict Simulation; Multipath	10/10/85, 10/15/85
.4.2	Antenna Coverage Test	Not Completed
4.4.7.1	Operational Flight Test - Data Collection	10/18/85
N/A	Deinstall TEU from S-76	10/21/85

DISCUSSION

TEST CONDUCT.

COMPASS SWING. This test combined the requirements of the compass swing, ramp test for antenna patterns, and ramp test for Angle of Arrival (AOA) accuracy.

The S-76 was taxied to the approach end of runway 17 (a closed runway) and parked over a compass rose. With the rotor turning, the aircraft was rotated in 15° increments. Aircraft support personnel were positioning the aircraft accurately and were noting actual aircraft heading. Inside the aircraft, logs of the magnetic compass (read from the pilot's and copilot's cards), TEU indicated bearing (read from the TEU processor display), and time of day were all kept.

STATIC ANTENNA PATTERN. This test was performed coincidently with the compass swing. As the helicopter was rotated for the compass swing, project personnel logged the voltage levels of received replies, read from an oscilloscope connected to the TEU video output port.

The test transponder in this experiment was located in the TCAS laboratory in the hangar building (FOB 301), with the antenna mounted on the roof of 301. Figure 1 shows the location of the compass rose and FOB 301.

From the coordinates shown in figure 1, the magnetic heading and range from the compass rose to FOB 301 was calculated (see "Detail" figure 1). Range was used to isolate replies of the test transponder from fruit, and bearing was used to normalize the pattern measurements to the nose of the aircraft.

STATIC AOA ACCURACY. The test plan definition of this measurement was a ramp test to be conducted on the ground. However, multipath was affecting the TEU bearing so severely that the test was meaningless. Instead, the helicopter was hovered at 100 feet above the compass rose and slowly rotated in a circle. The ship's compass was routed to the TEU and provided position reference. For calibration, a time mark was logged when the helicopter passed the point where the nose pointed directly at FOB 301.

Four complete revolutions were made by the helicopter; two with the top antenna connected (bottom antenna terminated) and two with the bottom antenna connected to the top antenna AOA processor.

AOA ACCURACY MEASUREMENT. This test was conducted per the definition in the test plan with one deviation; the range of the target aircraft was moved from 0.5 mile out to 1.0 mile. This change was necessary because the target was orbiting with wings level to keep the laser reflector always in view of the laser tracker. A 0.5-mile radius circle was too tight to achieve without banking the wings. Therefore, the radius of the orbit was increased to 1.0 mile.

ANTENNA COVERAGE. The test plan definition of this measurement included a video recorder to locate holes in the antenna coverage. The recorder was not used, although the end result is the same.

The requirements for this test were satisfied by the data from the AOA accuracy measurement. Azimuth and elevation pattern cuts were provided by the orbiting aircraft. Within the azimuth cuts, however, an additional level of data precision is available as a result of the granularity of the TEU whisper shout (WS) interrogation sequence. The WS sequence used in the AOA accuracy test has a dynamic range of 24 decibels (dB) distributed over 9 levels. Thus, a measure of received signal strength is implicit in the TEU interrogation sequence.

This test is critically dependent on maintaining "wings level" roll profiles of the S-76 and intruder aircraft to prevent signal fades due to shielding. Specific attention was paid to keeping both aircraft level while the intruder was orbiting the S-76.

ENCOUNTERS - MIDAIR CONFLICT SIMULATION. The encounter missions were completed per the test plan definition. Encounters with airborne targets were flown over the ocean near the coast of Sea Isle City, while encounters with aircraft landing or taking off were flown using the runway at the Woodbine, N.J., Airport.

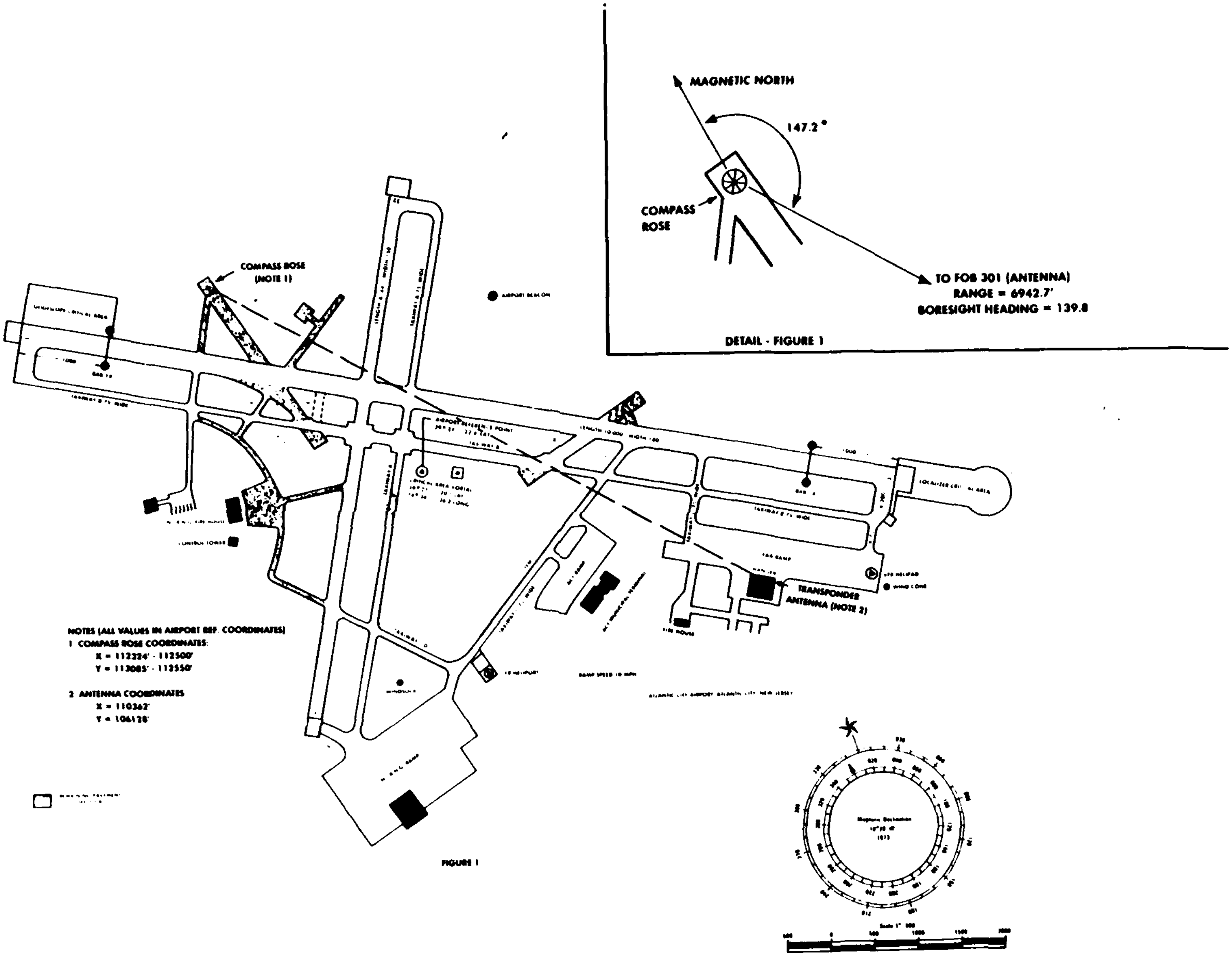


FIGURE 1. AIRPORT LAYOUT SHOWING RAMP TEST CONDITIONS

MULTIPATH TEST. This test was performed per the definition in the test plan. By design, the horizontal multipath test was performed over water at altitudes where reflected energy would be greatest. These same altitudes are typical of some commercial helicopter operations and coincide exactly with altitudes of the S-76 and threat aircraft in some of the encounters in the midair conflict simulation. Therefore, the results of those encounters can be added as test cases to the data base created from this experiment.

RESULTS

COMPASS SWING.

Errors in the TEU derived compass versus optical siting on the compass rose were measured as:

Peak to peak error less than 1.0°
Mean error = 0.065°
Sigma square error 0.201°

These errors are low enough to permit the S-76 compass to be used as a heading reference.

STATIC ANTENNA PATTERN.

Figure 2 shows the antenna patterns for the top (nose mounted) and bottom tail mounted antennas. The data are presented in dB relative to 1 milliwatt versus a linear azimuth scale. Received power level was determined using the receiver log video transfer function computed as power = 0.0258 X (video voltage) + 2.628.

STATIC AOA ACCURACY.

Figure 3 shows the results of the ramp AOA check. The diagonal line in the figures represent the reference bearing, and the measured bearing is shown relative to the reference. Note that the measured data is raw; no smoothing has been performed.

Figure 3 shows top antenna data which contain no bias offsets but which has been subtracted, point by point, from 360°. This compensates the direction of phase change across the antenna and matching networks. The bottom channel, also shown in figure 3, is bottom antenna data fed into the top antenna AOA processor. The data processing is the same.

In both figures, a value of 147.2° has been added to every point in the reference data set. This normalizes the reference data to the boresight heading of the test transponder.

In the upper right corner of each box in figure 3 are the values of mean error and variance (sigma squared). They represent figures of merit. The mean error represents the accumulated phase delay of TEU antenna, network electronics, and processing and is reducible. Variance is the noise in the antenna measurement and is also reducible, but to a lesser extent.

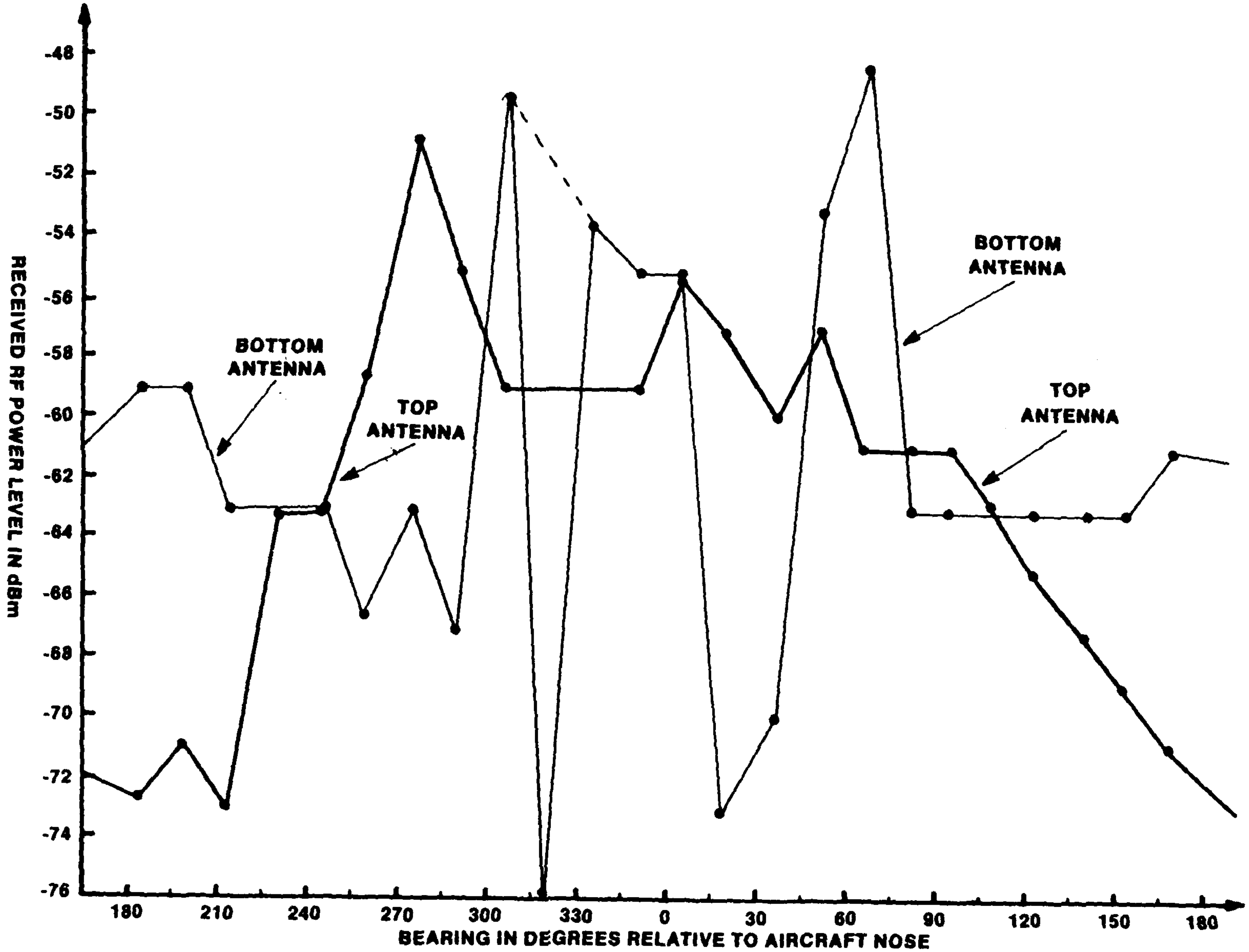


FIGURE 2. STATIC ANTENNA PATTERN

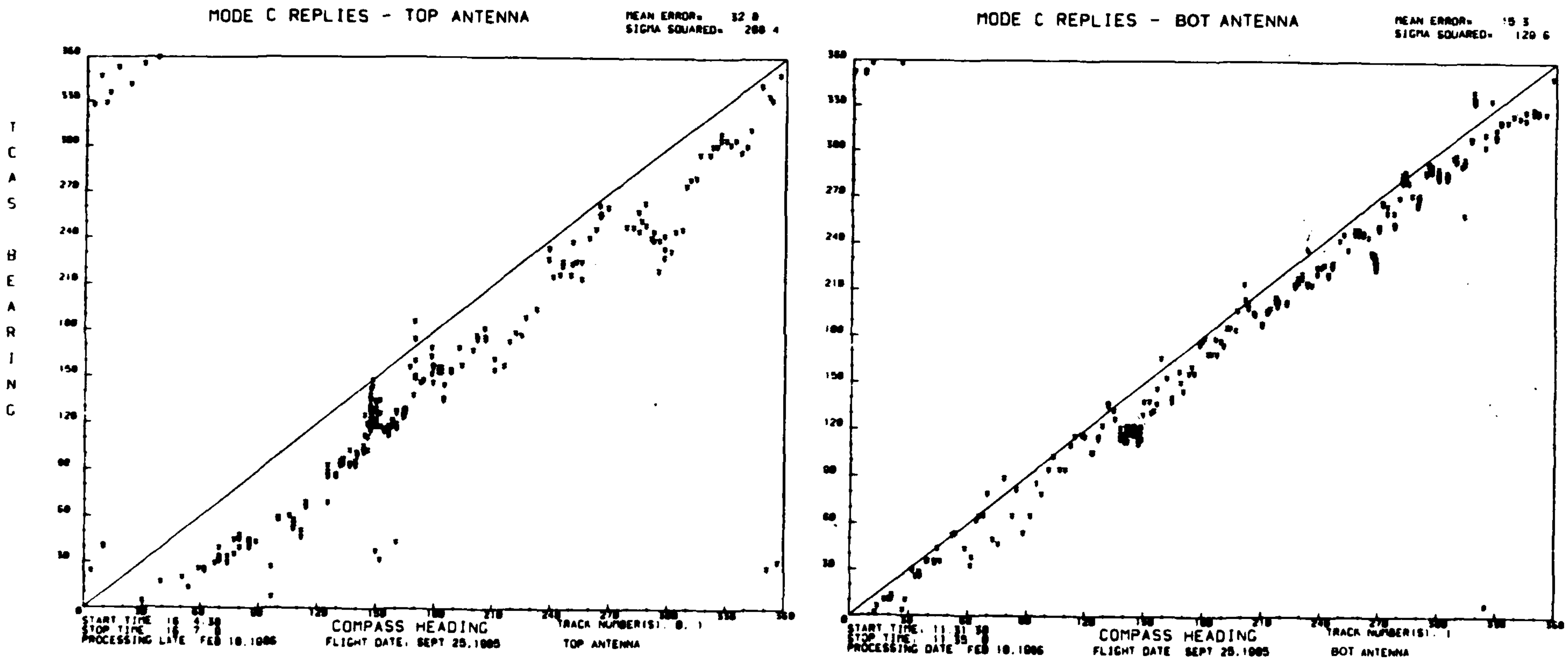


FIGURE 3. STATIC TCAS BEARING ACCURACY

Variance reduction (defined in equation 1) applied to the raw data will lessen the visible effect of the antenna noise. A theoretical variance reduction ratio (V_{rr}) of 0.211 resulting from smoothing has been demonstrated in reference 2. When the raw data was smoothed using Lincoln's bearing tracker, the resulting V_{rr} for the bottom antenna was 0.224 and 0.394 for the top antenna. The difference in the top and bottom antenna V_{rr} can be attributed to multipath corruption of the tracked data. For purposes of this report, a value of V_{rr} = 0.25 will be taken as attainable in a production TCAS.

$$\sigma^2 / \sigma_1^2 = \text{Variance Reduction Ratio } (V_{rr}) \qquad (1)$$

where σ^2 = variance of smoothed or tracking bearing data
and σ_1^2 = variance of raw bearing data

Application of V_{rr} to the ramp test data set results in the performance data shown in table 2.

TABLE 2. RESULTS OF RAMP AOA TEST

Antenna	Mean Error (Degrees)	Raw σ^2 (Degrees2)	Smoothed σ^2 (Degrees2)	Bearing Error one σ (Degrees)
Top	32	288.4	113.6	10.7
Bottom	15.3	129.6	29.0	5.4

AOA ACCURACY.

Flight test data are shown in appendix A. Each page depicts an orbit of the intruder aircraft whose relative altitude ranges from +1000 to -1000 feet in 250-foot increments. At the extreme relative altitudes, the elevation angle subtended from the plane of the S-76 to the plane of the intruder was $\pm 7.8°$.

Tables 3 and 4 summarize the data shown in appendix A.

TABLE 3. RESULTS OF AOA FLIGHT TEST - TOP ANTENNA

Run	Relative Altitude Feet*	Mean Error Degrees	Raw σ^2 (Degrees^2)	Smoothed σ^2 (Degrees^2)	Bearing Error one σ (Degrees)
1	0	23.2	255.5	63.9	8.0
2	0	21.9	247.7	61.9	7.87
3	-250	19.3	342.0	85.5	9.25
4	-250	27.0	274.0	68.5	8.28
5	-500	20.1	861.0	215.0	14.67
6	-500	31.4	619.8	154.9	12.45
7	-750	25.5	464.2	116.1	10.77
8	-750	28.9	405.2	101.3	10.06
9	-1000	25.1	296.8	74.2	8.61
10	-1000	22.7	221.2	55.3	7.43
11	+250	26.5	243.2	60.8	7.8
12	+250	24.5	209.1	52.3	7.23
13	+500	21.6	159.7	39.9	6.31
14	+750	21.1	636.5	159.1	12.61
15	+1000	21.7	598.8	149.7	12.23

*Minus relative altitude means intruder below.

TABLE 4. RESULTS OF AOA FLIGHT TEST - BOTTOM ANTENNA

Run	Relative Altitude Feet	Mean Error Degrees	Raw σ^2 (Degrees^2)	Smoothed σ^2 (Degrees^2)	Bearing Error one σ (Degrees)
1	0	-38	70.2	17.55	4.2
2	0	-36.7	118.1	29.52	5.4
3	-250	-41.4	82.9	20.7	4.55
4	-250	-40.5	54.9	13.72	3.7
5	-500	-39.9	71.2	17.8	4.21
6	-500	-41.9	48.0	12.0	3.46
7	-750	-40.8	54.9	13.73	3.7
8	-750	-39.5	55.4	13.8	3.72
9	-1000	-39.4	48.2	12.05	3.47
10	-1000	-41.0	78.5	19.6	4.4
11	+250	-43.7	45.9	11.5	3.38
12	+250	-43.8	57.4	14.35	3.78
13	+500	-40.9	147.5	36.88	6.07
14	+750	-40.7	50.9	12.7	3.6
15	+1000	-41.1	210.5	52.6	7.25

Tables 3 and 4 contain two values which influence the total bearing error. The first value is the spread in the mean error. For the top antenna, the mean error ranges from 19.3 to 31.4 as a function of elevation. If a value of 23.29° (geometric mean) were chosen as an overall bias, the peak to peak shift in the mean becomes +8.11/-7.79°. The calculated bias for the bottom antenna would be 40.58° for a peak to peak shift of +3.22/-3.88°.

The accumulated AOA error due to noise (variance) and due to a shift in the mean data is expressed as root-mean-squared (rms) error:

$$\mathrm{RMS} = \sqrt{\sigma^2 + \mu^2} \tag{2}$$

Using equation 2, the top antenna rms error was computed as a function of elevation. The results range from a minimum 6.5° rms at +4.5° elevation, to a maximum of 15.0° rms at -4° elevation.

Bottom antenna accumulated error versus elevation is: minimum rms error = 3.66° at +5.5° elevation, to a maximum of 7.27° at +7.8° elevation. The rms error versus elevation for both antennas is shown in figure 4.

Two effects are visible in the appendix A data. In the top antenna data, cyclic errors are apparent from 240° to 260°. The same effect is seen in the ramp AOA test data shown in figure 3. In both test sets, the helicopter's rotor was turning.

The bottom antenna data from appendix A does not exhibit the cyclic variation, but does contain prounounced dips at 110° and 220°. This same effect is seen in the ramp test data shown in figure 3.

In the ramp test, both antenna channels were fed into the top antenna reply processing circuitry. Therefore, the cyclic errors in the top antenna and the dip in the bottom antenna are both characteristics of the antenna systems and not the reply processing.

Lincoln Lab has observed cyclic errors in each of their top antenna installations on a Bell 206 Longranger. They have attributed those errors to interaction with the rotating cylinders used to control the main rotor (reference 3 and 4). MIT reports a periodicity of 33° when the interfering surface is 40 inches away from the TCAS antenna, and 20° when the interfering surface is 20 inches from the TCAS antenna. The periodicity in the Technical Center's data is approximately 30°. Figure 5 shows that the S-76 antenna is installed at station 42, and the base of the glare shield is at station 59, approximately 20 inches apart. The glare shield is metallized and is a reflector at L band. These results are consistent with MIT's results.

The dips in the bottom antenna data result from the geometry of the installation. Because the antenna is mounted on the tail boom which tilts slightly upward, the cabin of the helicopter forms a large obstruction which causes edge diffraction.

The computed results show that the top and bottom antenna rms errors produce a traffic advisory display whose indicated bearing is less than 1 o'clock position in error. Flight experience verifies these results for geometries where the bearing rate is smooth and established. The displayed bearing error can be larger if the intruder approaches at essentially zero bearing rate from

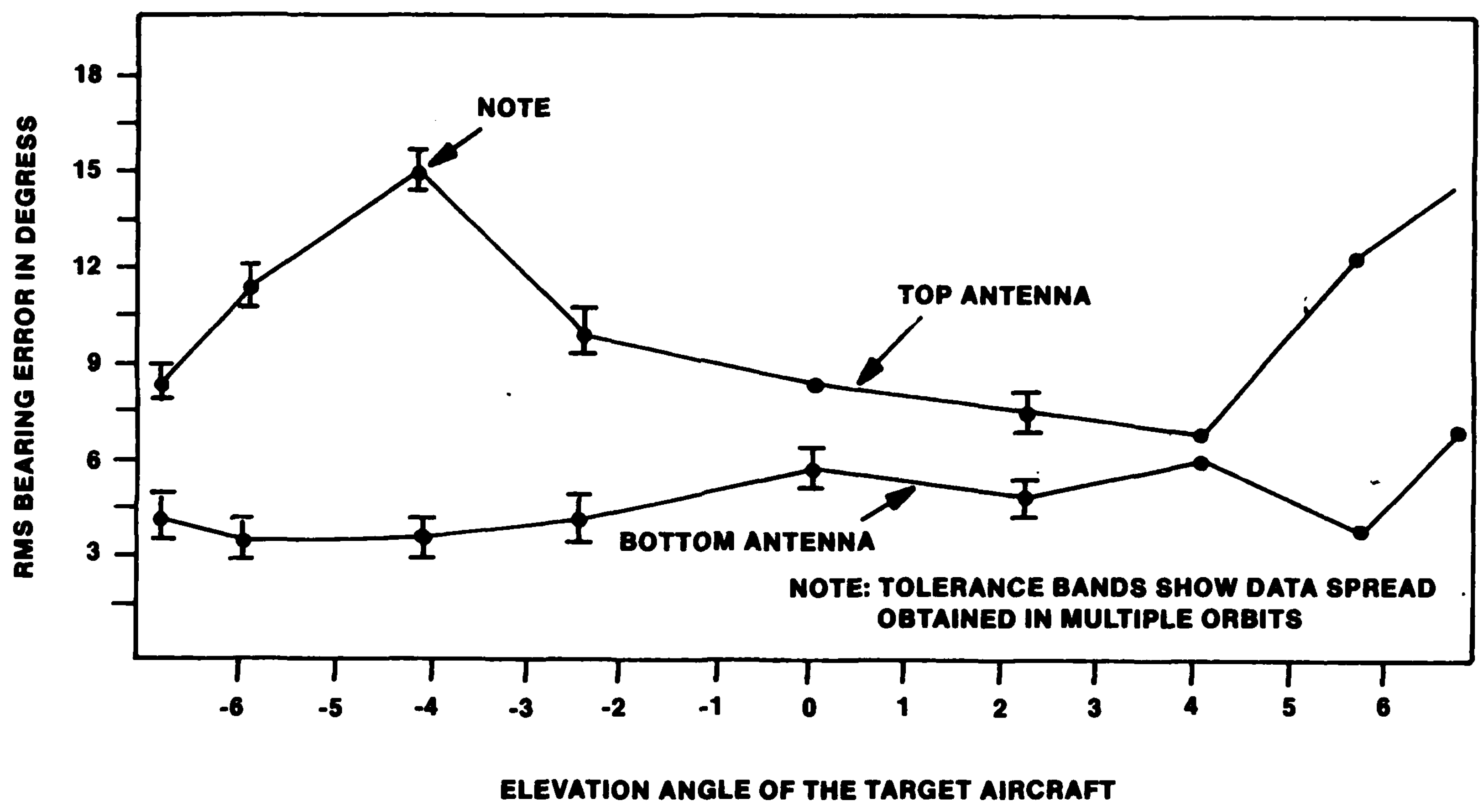


FIGURE 4. BEARING ACCURACY VERSUS ELEVATION ANGLE

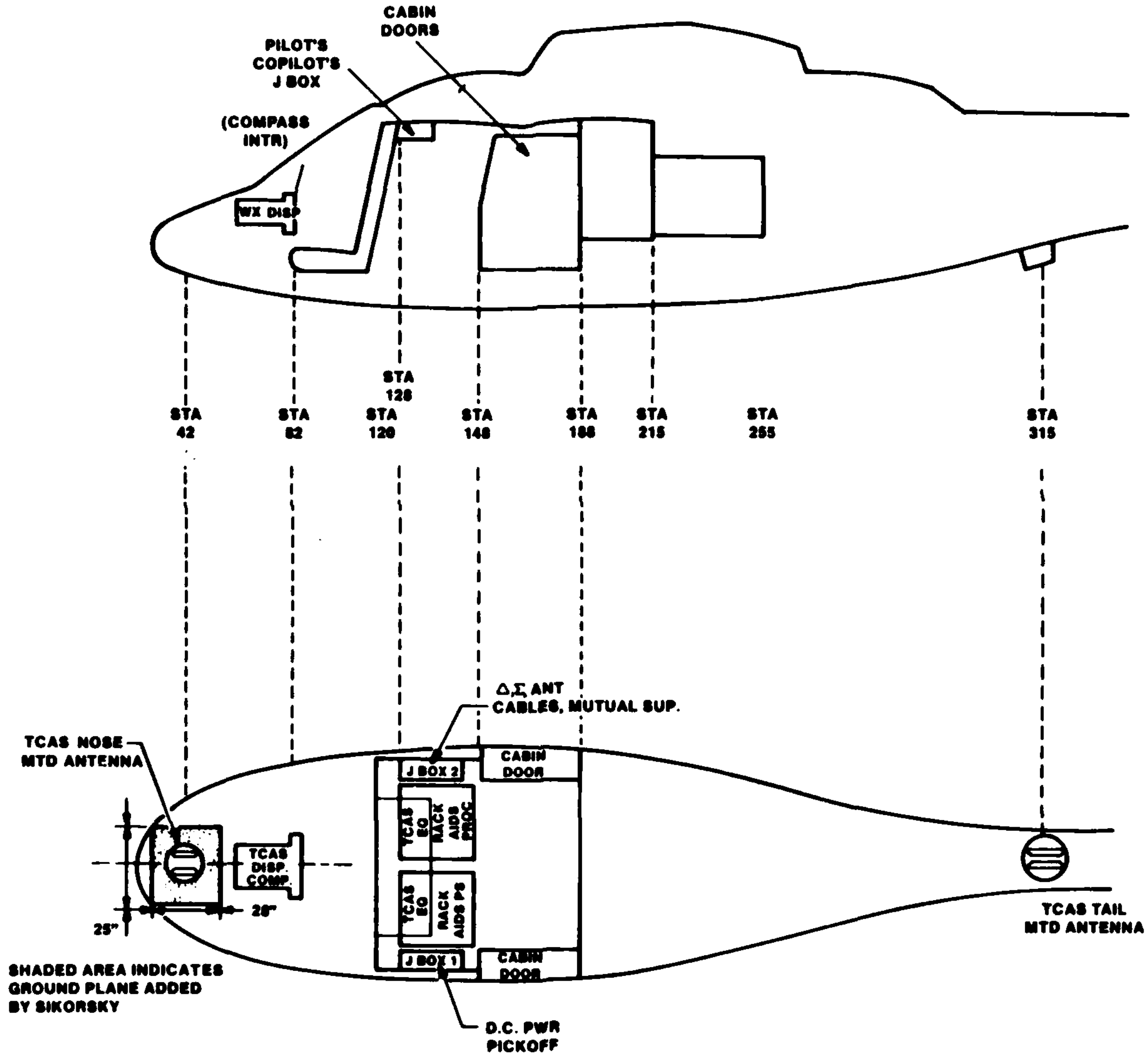


FIGURE 5. TOP AND BOTTOM TCAS ANTENNA LOCATIONS ON N-38

directions of higher error. For the top antenna these directions are centered at +45° relative to the nose (see top antenna data - appendix A). Around 345° the AOA behavior would alternately lag and then accelerate relative to the visual scene. Depending upon the initial intruder position, the bearing may precess slightly retrograde to the visual scene before correcting itself.

Around 45°, the top antenna AOA shows a flat spot which would result in a bearing lag relative to the visual scene. Depending upon the initial conditions, the displayed bearing can be a clock position in error.

ANTENNA COVERAGE.

Data for the analysis of antenna coverage is contained in appendix B. Figures B-1 through B-4 show the range, altitude, and AOA of the target aircraft as it completed four orbits. Figure B-1 shows run 7 which is the extreme case of the negative elevation angle orbits (-7.8°); figure B-2 shows a repeat run. Figure B-3 shows a nearly coaltitude run (run 7); figure B-4 shows the extreme positive elevation orbit +7.8°.

The lower plot of each figure, the AOA plot, shows TEU indicated bearing "*", and reference bearing "C" derived from the ground trackers. This plot is used to correllate time with range and bearing in each orbit.

Figures B-5 through B-12 show all WS levels which contain replies plotted as a function of azimuth. As shown in figures B-5 through B-8, replies from the top antenna are generally received on WS level 5. This result is expected for two reasons: (1) WS level 5 employs no suppression pulses, and (2) an analysis contained in reference 5 defines the expected reply range of 0 to 2.2 nautical miles for this interrogation.

Figures B-9 through B-12 indicate that replies on the bottom antenna are generally received on WS levels 1 and 14. Neither of these levels employ suppression. Reply density will be higher in WS 14 relative to WS 1 because it is a higher power interrogation by 10 dB.

The patterns of the top and bottom antennas are inferred by observing the "envelope of the dots" in figures B-5 through B-12. The envelope is formed by using the lowest WS level as a baseline and referencing the other WS levels to it. For example, in B-5, WS 5 forms the baseline (see equation 3). Between 150° and 270°, the reply density shifts from WS 5 to the higher WS levels. At 180°, replies seem clustered in WS 7 and 8; between 210° and 240°, the cluster is found in WS level 9. This variation dictates a signal path attenuation of approximately 8 dB (reference 5), see equation 4. To account for signal attenuation due to slant range it is necessary to examine B-1. Between 180° and 270° (read from the compass heading scale) the target range (top plot) varied from approximately 1.5 to 2.0 nautical miles (nmi), accounting for 1.2 dB of path attenuation (see equation 5). Thus, the antenna pattern variation in this example is approximately 8 - 1.2 = 6.8 dB. Equations 3 through 6 define the analysis and table 5 shows the results of each of the four runs.

S = Baseline RF link calibration
S = (Suppression power of baseline - WS Level + 1) (3)

A = RF path attenuation
A = (Interrogation power of WS evelope) - (S) (4)

"A" must be normalized for range variations:

A' = RF pattern variation

$$A' = A - 10 \, \text{Log}(R_{max}/R_{min}) \qquad (5)$$

where Rmax and Rmin are the minimum and maximum target ranges over the interval of interest

The total antenna pattern variation is expressed as (6).

$$V = A - S - A' \qquad (6)$$

It is important to note that no account has been made for RF path variation due to intruder aircraft turning and resulting wings/fuselage shielding. To eliminate this effect, the test plan required the intruder to execute turns using the rudder control only with virtually no wing banking. The technique appears successful because the RF variation is correllated in target bearing and is not observed randomly.

TABLE 5. ANTENNA PATTERN AMPLITUDE VARIATION VS AOA

Elevation Angle (Degrees)	Antenna	Maximum Variation	AOA Range From	AOA Range To	Comments
-6.5	Top	7.8	180	240	6.8 dB variation at 30°
-6.5	Bot	6.8	240	60	4.0 dB variation at 90°
0	Top	5.8	180	240	gap at 30° due to data loss
0	Bot	3.8	210	270	
+6.5	Top	6.8	150	270	gap at 180° due to tracker loss
+6.5	Bot	6.8	210	270	

Antenna pattern variation in the top antenna is clearly in the range 180° to 240°. The reason for this is in the location of the top antenna. Figure 5 shows that the top antenna is mounted to the right of the aircraft centerline. Therefore, the region of maximum shielding is rearward and slightly left of the aircraft.

The bottom antenna is mounted on the aircraft centerline. Pattern variation is more symmetrical, centered in the 45° and 315° azimuths.

Predicted antenna pattern data taken from reference 5 is shown in appendix C.

MULTIPATH.

A total of 16 runs were flown to create sustained and transient periods of multipath. Both tracked and raw reply data were analyzed to: (1) determine effectiveness of the multipath elimination schemes developed at the MIT Lincoln Laboratory and (2) examine additional techniques to further reduce evidence of multipath.

MIT Lincoln uses reply level processing and track level computations to eliminate multipath tracks. At the reply level, correlating replies are organized by range. Only the shortest range replies are used in track formation or extension. At the track level, own aircraft barometric altitude is used to compute likely range and range rate conditions of multipath tracks for each "real" track in surveillance. Only a track that meets the computed geometric conditions (in addition to a condition on track age) is deleted.

The Lincoln technique works well especially when flying over terrain at or near sea level where own barometric altitude is nearly the aircraft height above ground.

In a review of the Technical Center's flight data, the following observations were noted:

1. Building and ground (vertical and horizontal) reflections have similar characteristics in range and altitude. They differ in bearing rate, however. The differential bearing rate between real and ground reflected replies is very small. The differential bearing rate between real and building replies can have a component created by the velocity of the aircraft. Furthermore, the bearing rate of the real replies can be opposite sense to the rate of the reflected replies.

2. When the reflecting surface is water or land, the bearing of the reflected replies is definitely clustered.

3. Due to the lower helicopter altitudes, multipath is most difficult to detect at target ranges of approximately 1 mile or less.

4. At target ranges of 1 mile or less, reply efficiency increases two or three fold. For example, it is common to observe two or three replies in 22 WS levels (each second) for distant targets. At a mile or less the number of received replies can be as high as nine.

5. Multipath replies can be produced either in the interrogation path or in the reply path. The graduated power output of the WS sequence is effective in reducing interrogation link reflections in the lower power WS levels.

6. The bearing data in the lower power WS steps (see observation 5) is usually closest to the true target bearing.

7. MIT Lincoln Laboratory's technique of deleting replies with illegal (and nonzero) interior code pulses (reference 6) is effective in reducing the incidence of non-Mode C replies produced by altitude code corruption.

8. In general, the number of non-Mode C multipath produced replies is low. Of those produced, about half lack resolvable bearing data.

These observations lead naturally to an algorithm which will be used in processing Group 3 flight data. The key elements of the algorithm are listed below:

1. As replies are received, sort by range and WS number, lowest first.

2. Form target reports using replicated replies. The reply received on the lowest WS level should be used as the most likely real reply.

3. At target ranges of 1 mile or less, correllate on range, altitude, and bearing, especially when using bottom antenna data.

4. Non-Mode C replies that have no resolvable bearing should be eliminated.

5. At target ranges of 1 mile or less, correlate intra-WS level replies that fit two different tracks but continue to appear in the same WS level.

ENCOUNTERS - MIDAIR CONFLICT SIMULATION.

INTERROGATE-REPLY LINK. Over a target range of 4.0 nmi, high probability of reply (P_r) exists using only WS levels 5 (top antenna) or 14 (bottom antenna). These levels correspond to 41.2 decibels above one milliwatt (dBm) (top) and 39.1 (bottom) interrogation power measured at the transmitter output.

The following conditions were observed from the flight test:

1. 4.0 nmi surveillance range.

2. Target aircraft transponder sensitivity = -75.5 dBm.

3. A lower power 4 level WS sequence transmitted on the bottom antenna showed that the target transponder was at least 3 dB above minimum triggering level (MTL), (MTL headroom) when answering WS levels 5 and 14.

From these observations, a minimum interrogator power requirement can be established.

Pwr = 41.2 dBm -3 dB (3 dB is MTL headroom)
= 38.2 dBm

From the previous section, the antenna gain variation over azimuth and elevation is 7.8 dB

Pwr = 38.2 dBm + 7.8 dB
= 46.0 dBm

Free space attenuation at 4.0 miles is 6 dB greater than 2.0 miles. In the forward direction, antenna gain compensates the free space loss. In the aft direction, reliable coverage is possible out to a range of 2.8 miles.

The specified general aviation transponder sensitivity ranges from -69 to -77 dBm at the antenna terminals. Thus, for the top antenna system:

Pwr = 46.0 dBm + -69 dBm - (-75.5 dBm)
= 52.5 dBm (177.8 watts)

For the bottom antenna, the necessary interrogator power is:

$$\begin{aligned} Pwr &= 39.1 \text{ dBm} - 3 \text{ dB (MTL headroom)} \\ &= 36.1 \text{ dBm} + 8 \text{ dB (pattern variation)} \\ &= 44.1 \text{ dBm} + -69 \text{ dBm} - (-75.5 \text{ dBm}) \\ &= 50.6 \text{ dBm (114.8 watts)} \end{aligned}$$

The necessary TCAS receiver sensitivity is determined in a similar way. General aviation transponders are required to transmit replies at power levels between 48.5 and 57 dBm measured at the antenna.

At 4.0 nmi, the aggregate loss in the interrogate/reply link is:

Loss (Top antenna) = 110 dB free space + 3.7 dB net cable loss

Loss (Bottom antenna) = 110 dB free space + 1.6 dB net cable loss

The received signal strength at the antenna is:

$$\text{Top Antenna: } R = 48.5 \text{ dBm} - 110 \text{ dB} - 3.7 \text{ dB} = -65.2 \text{ dBm}$$

$$\text{Bottom Antenna: } R = 48.5 \text{ dBm} - 110 \text{ dB} - 1.6 \text{ dB} = -63.1 \text{ dBm}$$

The required receiver sensitivities, after accounting antenna gain variation are:

$$\text{Top Antenna} \quad S = -65.2 \text{ dBm} - 7.8 \text{ dB} = -73.0 \text{ dBm}$$

$$\text{Bottom Antenna} \quad S = -63.1 \text{ dBm} - 7.8 \text{ dB} = -70.9 \text{ dBm}$$

It should be noted that the antennas manufactured by Dorn and Margolin exhibit a gain of approximately +5 dBi at peak of beam. The derived values of transmitter power and receiver sensitivity are based on this antenna performance.

INTERFERENCE LIMITING.

MIT Lincoln Laboratory has developed an interrogation power limit, expressed in watts per second, which limits the total radiated power (TRP) transmitted by TCAS I in higher aircraft density. One scheme proposed by MIT is to increase the interrogation period from the present value of 1 second. In their preliminary experiment, they have found success in a 4-second scan period (tracking Mode C targets of opportunity). By using a longer scan period, the peak power of the interrogation sequence can be maintained at a reasonably high power level since the TRP is averaged over 4 seconds.

In increasing the scan period, MIT had to expand the range correlation windows and adjust the alpha and beta coefficients in their tracker.

MIT has reported a high probability of track (PT) and reasonably low false track rate for Mode C targets that pass within 1.5 miles and +/-900 feet of the TCAS I aircraft. Mode C targets afford two-track correlation parameters, range, and altitude.

Non-Mode C aircraft do not reply with altitude information. Therefore, only one-track parameter, range, is available. With the expanded track correlation windows resulting from the increased scan rate period, non-Mode C false track generation may become excessive.

The next section of this report dicusses the feasibility of using bearing as an additional correlation parameter for Mode C and non-Mode C tracks.

TOP VS BOTTOM ANTENNA SELECTION.

By now, the performance of the top and bottom antennas is understood well enough so that the relative merits of each installation can be considered.

The antenna parameters considered in this discussion were:

1. Probability of reply (antenna coverage)
2. Susceptibility to multipath
3. Bearing accuracy (antenna pattens)

Both antennas yield acceptable performance in reply efficiency. There are no holes in coverage which cause blind spots in the TCAS protection volume.

The bottom antenna is more susceptible to multipath. This has been demonstrated at length in several programs at the MIT Lincoln Laboratory, and is shown again for convenience in figure 6. With so much multipath, the effect of the WS sequence in deoverlapping replies is diminished. In addition, the false track rate becomes higher.

Bearing accuracy in the bottom antenna is approximately two times better than the top antenna. With accuracies of 7° rms, the bottom antenna yields bearing which is good enough to be used as a track correlation parameter, considering that the two-sigma spread in the error data is less than 15°. By contrast, the two-sigma spread in the top antenna is over 30°.

The top antenna is less susceptible to multipath, but has poorer bearing performance.

In determining an antenna site on the helicopter, the choice is bearing accuracy versus increased false track activity due to multipath.

One additional area where increased bearing accuracy is useful is in horizontal miss distance (HMD) calculations applied to false traffic advisory (TA) reduction (reference 7). The feasiblity of HMD filtering for the top and bottom antennas will be examined using Group 3 flight data. The relative merits of HMD filtering will be considered in the top antenna versus bottom antenna selection.

SUMMARY OF RESULTS

ANTENNA COVERAGE.

The antenna patterns measured in the ramp test are similar to those derived in the flight check.

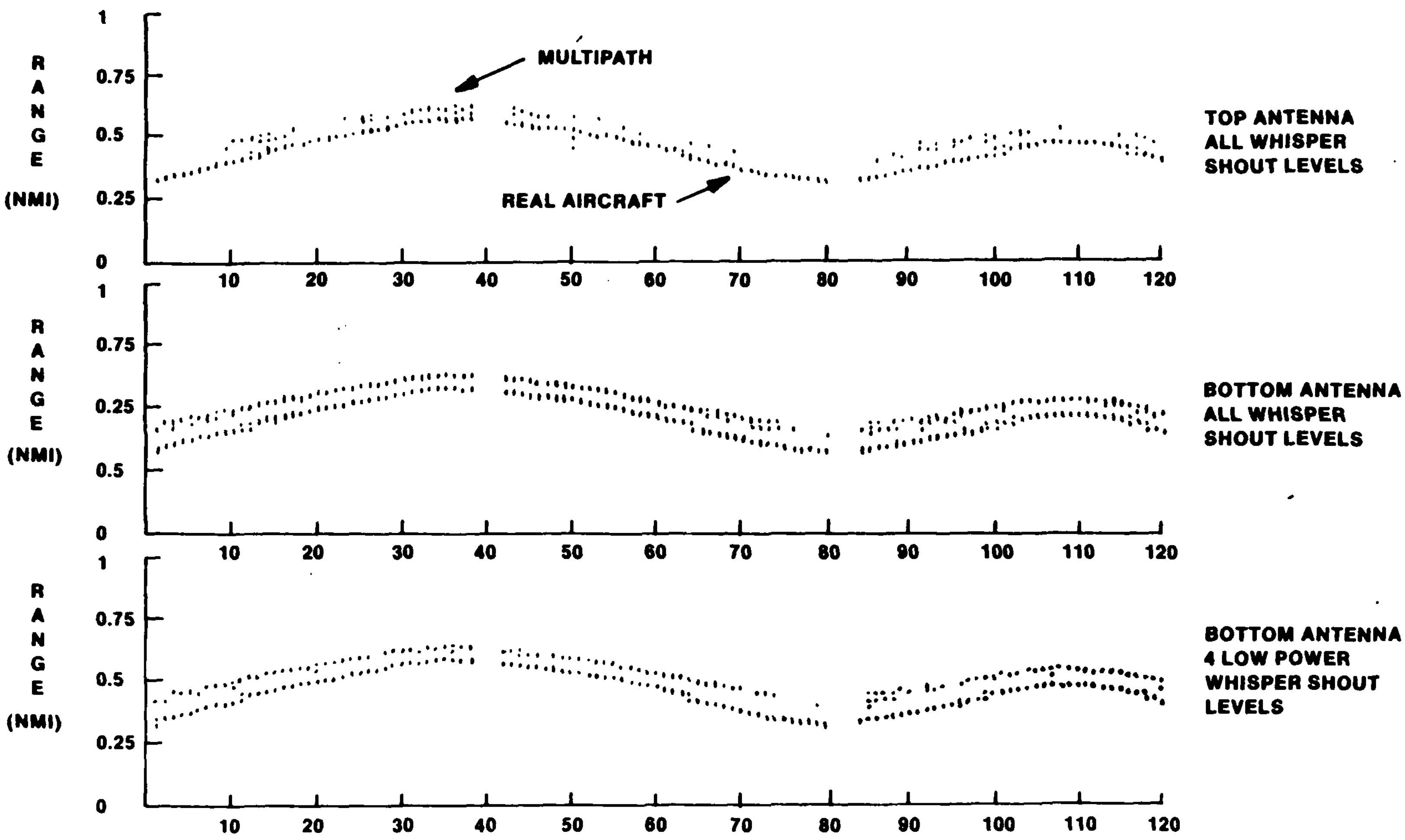


FIGURE 6. REAL AND MULTIPATH REPLIES - TOP ANTENNA-BOTTOM ANTENNA COMPARISON

Maximum attenuation in the top antenna pattern, measured in the ramp test, occurs from 180° to 210°. Pattern rolloff occurs from 105° to 180° and from 210° to 215°. Pattern attenuation derived from the flight test extends from 180° to 240° in the coaltitude runs, and from 150° to 240° at the extremes of elevation angle.

Maximum attenuation in the bottom antenna, measured in the ramp test, occurs from 240 to 270°, and again at 30°. By contrast, the coaltitude orbit of the flight check illuminated attenuation from 210° to 270° and from 240° to 60° at the extremes of elevation.

Pattern attenuation measured in the top antenna was 11 dB (ramp test), and 7.8 dB + 3 dB (headroom) = 10.8 dB (flight check). Pattern attenuation in the bottom antenna was 13 dB (ramp test) compared to 6.8 dB + 3 dB headroom = 9.8 dB flight check. These values are based on a reference level of -63 dBm.

Appendix C data show good agreement with the flight data in the forward looking hemisphere of each antenna (over a range of ±7.8° elevation angle). Beyond those regions, the predicted attenuation in appendix C is approximately 15 dB higher than the flight data.

AOA ACCURACY.

The results of the ramp test and two coaltitude runs of the flight test are shown in table 6.

TABLE 6. RAMP AND FLIGHT TESTS AOA RESULTS

	Mean Angle Error			Variance		
	Ramp	Run 1	Run 2	Ramp	Run 1	Run 2
Top Antenna	32°	23.2°	21.9°	288.4	255.0	247.7
Bottom Antenna	15.3°	-38.0°	-36.7°	129.6	70.2	118.1

The results show agreement in the top antenna data. However, the mean error in the bottom antenna is different by 45° in the ramp data compared to the flight data. This difference is due to the test configuration. In the ramp test, the bottom antenna was connected to the top antenna AOA processor, whereas, in the flight check, each antenna was connected to its own processor. The variance in the bottom antenna data is consistent in the ramp and flight tests.

MULTIPATH.

The flight data showed three characteristics of multipath which are not exploited in current multipath elimination algorithms. Five recommendations were made based on the observed characteristics. See "Results - Multipath" for details.

ENCOUNTERS - MIDAIR CONFLICT SIMULATION.

Based on the flight data, TCAS RF characteristics were derived. A minimum interrogator power of 177.8 watts top antenna or 114.8 watts bottom antenna, and receiver sensitivities of -62.5 dBm top antenna and -63.1 dBm bottom antenna will provide adequate surveillance coverage out to 4 miles in front and 2.8 miles in back. This coverge applies to the specified performance of general aviation transponders.

CONCLUSIONS

1. The Sikorsky S-76 magnetic compass system is accurate enough to be used as a heading reference.

2. Ramp test data compared for antenna coverage and bearing accuracy compare favorably to flight test data. The two test sets are within 3.2 decibels (dB) in patterns and 10° in bearing.

3. The performance of the two antennas on the S-76 has been characterized, and either antenna will work as the primary antenna in a TEU installation.

4. The bottom antenna is approximately two times better than the top antenna in bearing error (7° versus 15° root-mean-square (rms)), but is more susceptible to multipath.

5. In Group 3 data analysis, horizontal miss distance (HMD) filtering applied to traffic advisory (TA) reduction will be examined. The relative benefit of HMD filtering will affect the selection of a top antenna versus bottom antenna TCAS configuration.

RECOMMENDATIONS

1. Proceed with Group 3 flight testing per the test plan (reference 1).

2. Implement the multipath elimination algorithm described in this report for evaluation using Group 3 flight data.

REFERENCES

1. Rehmann, Albert J., Test Plan for Rotorcraft Traffic Alert and Collision Avoidance System (TCAS), DOT/FAA/CT-TN85/49, FAA Technical Center, December 1985.

2. Sinsky, A.I., ALPHA-BETA Tracking Errors for Orbiting Targets, BCD-TN-81-033, Bendix Corporation, June 1981.

3. Harman, William H., Letter, Installed Antenna Gain, RTCA Paper 14-86/SC147-195, William H. Harman, MIT Lincoln Laboratory, January 6, 1986.

4. Hartenstein, Richard G., Analysis of Airborne Antenna Systems Using Geometrical Theory of Diffraction and Moment Method Computer Codes, Report No. 716199-6, The Ohio University Electroscience Laboratory.

5. Comish, I.W., Jr., Azimuth and Elevation Plane Patterns of 4 Antenna Locations - Sikorsky S-76, BASIC MLS-TN026, Bendix Corporation, July 27, 1982.

6. Wood, Loren M., Algorithm for TCAS II Tracking of Non-Altitude - Reporting Aircraft, 42PM-TCAS-0038, The Massachussetts Institute of Technology (MIT) Lincoln Laboratory.

7. Mulder, Steven J. and Spencer, Ned A., Horizontal Miss Distance Filtering, RTCA Paper 197-86/SC147-205, The MITRE Corporation, May 7, 1986.

APPENDIX A

AOA ACCURACY PLOTS

Figure		Page

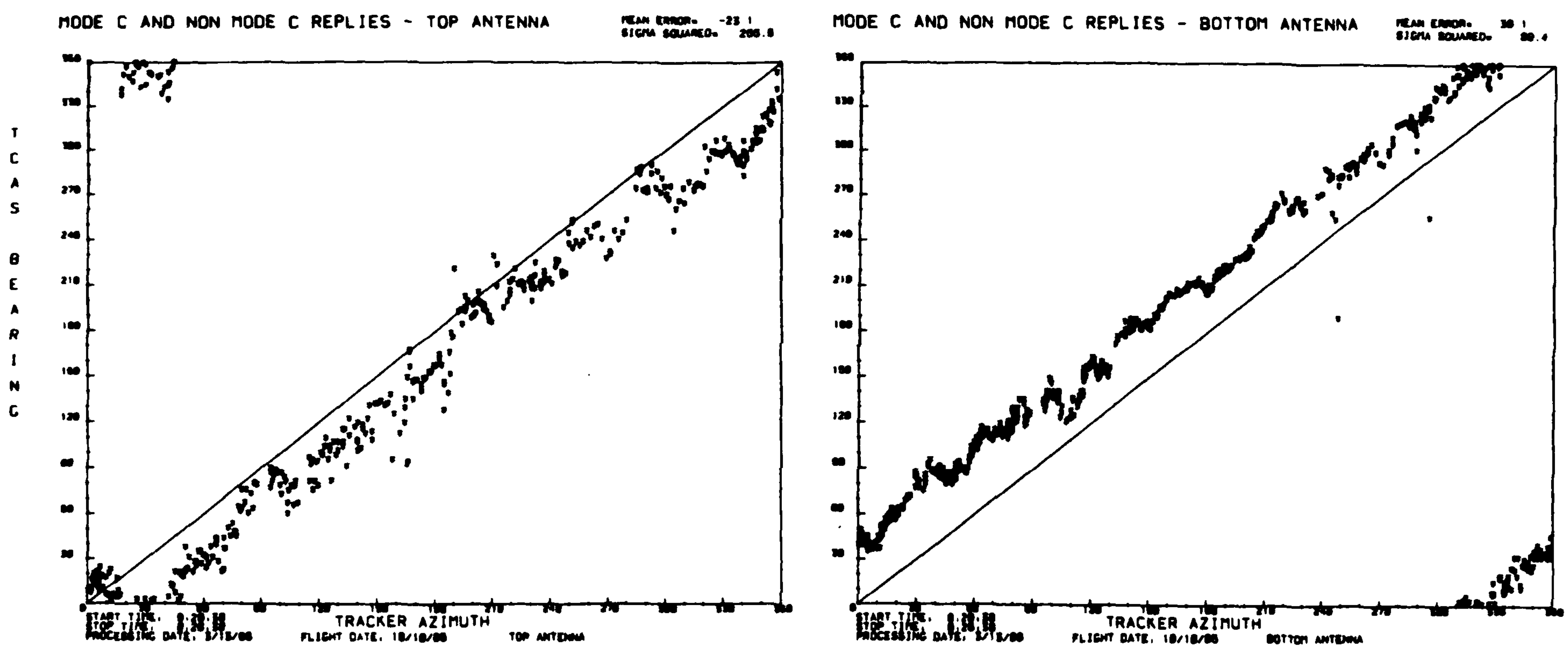


FIGURE A-1. TCAS BEARING VS TRACKER AZIMUTH, RUNS 1 AND 2 - INTRUDER COALTITUDE

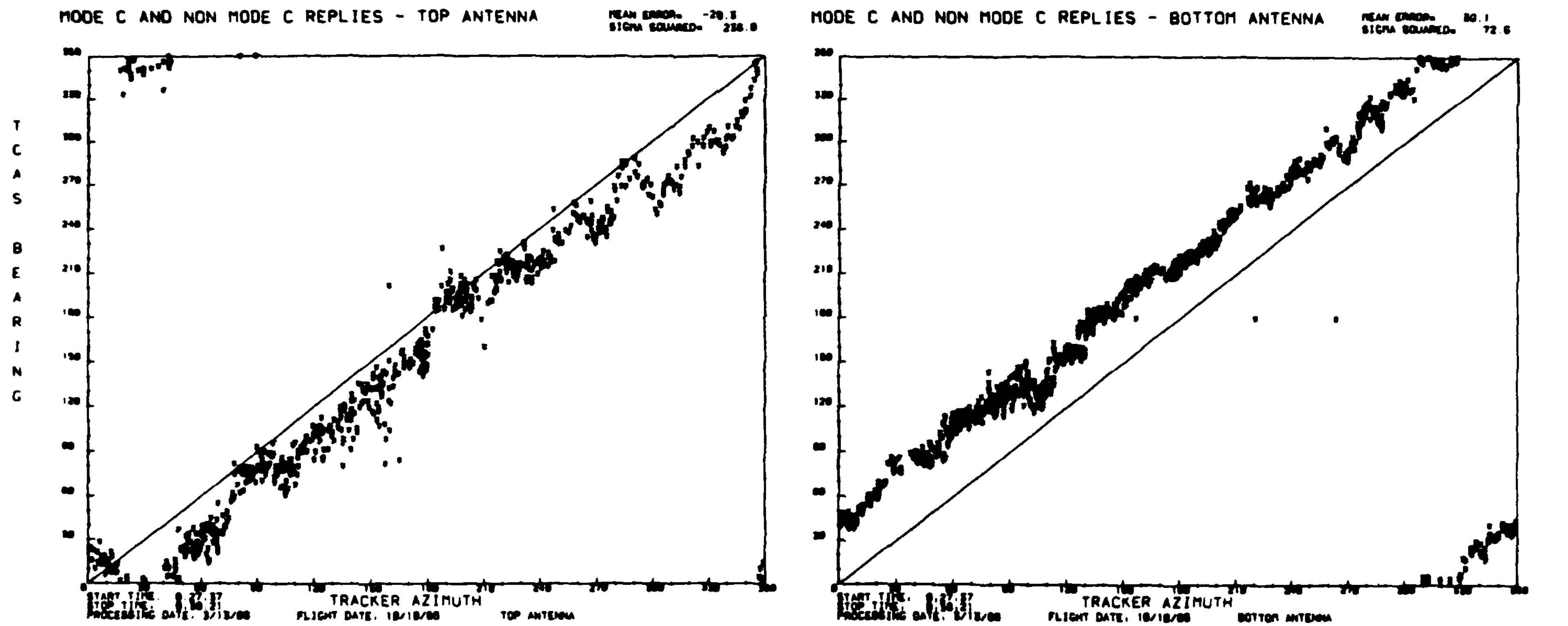


FIGURE A-2. TCAS BEARING VS *TRACKER AZIMUTH, RUNS* 3 AND 4 - INTRUDER 250 FEET BELOW TCAS

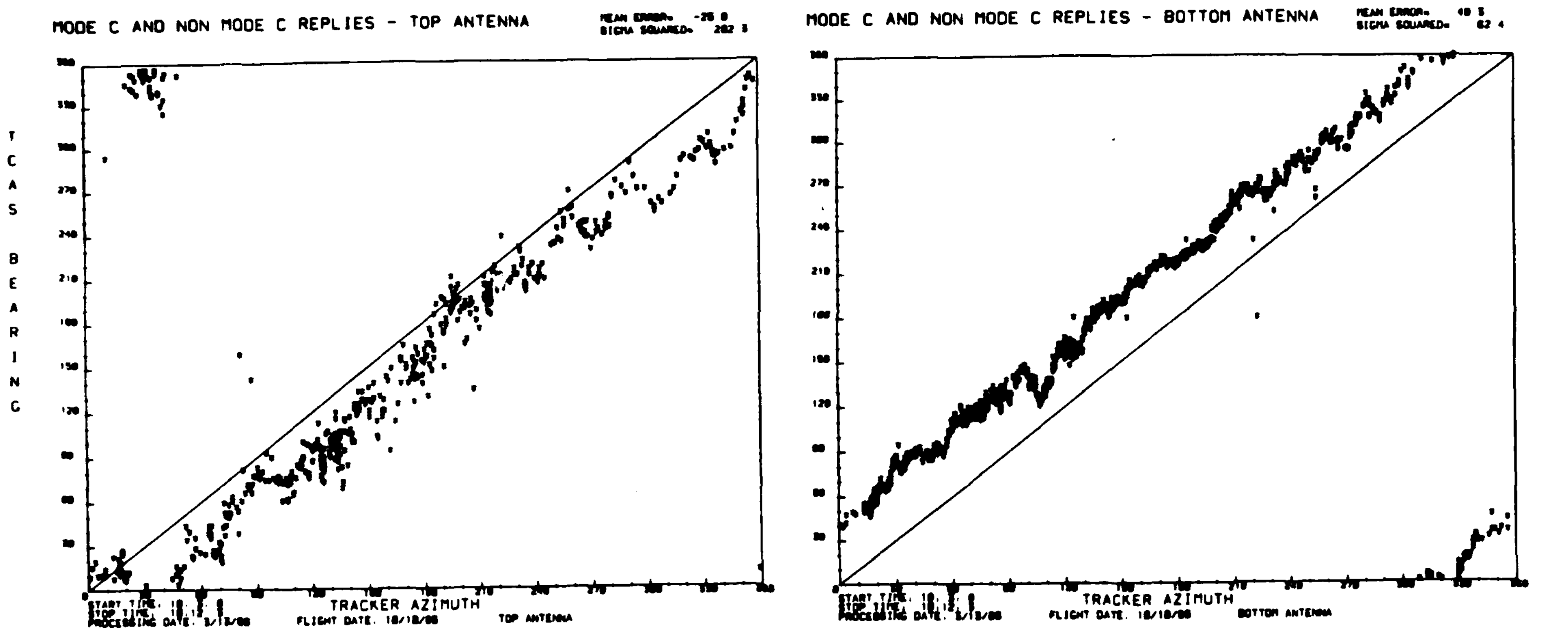


FIGURE A-3. TCAS BEARING VS TRACKER AZIMUTH, RUNS 5 AND 6 - INTRUDER 500 FEET BELOW TCAS

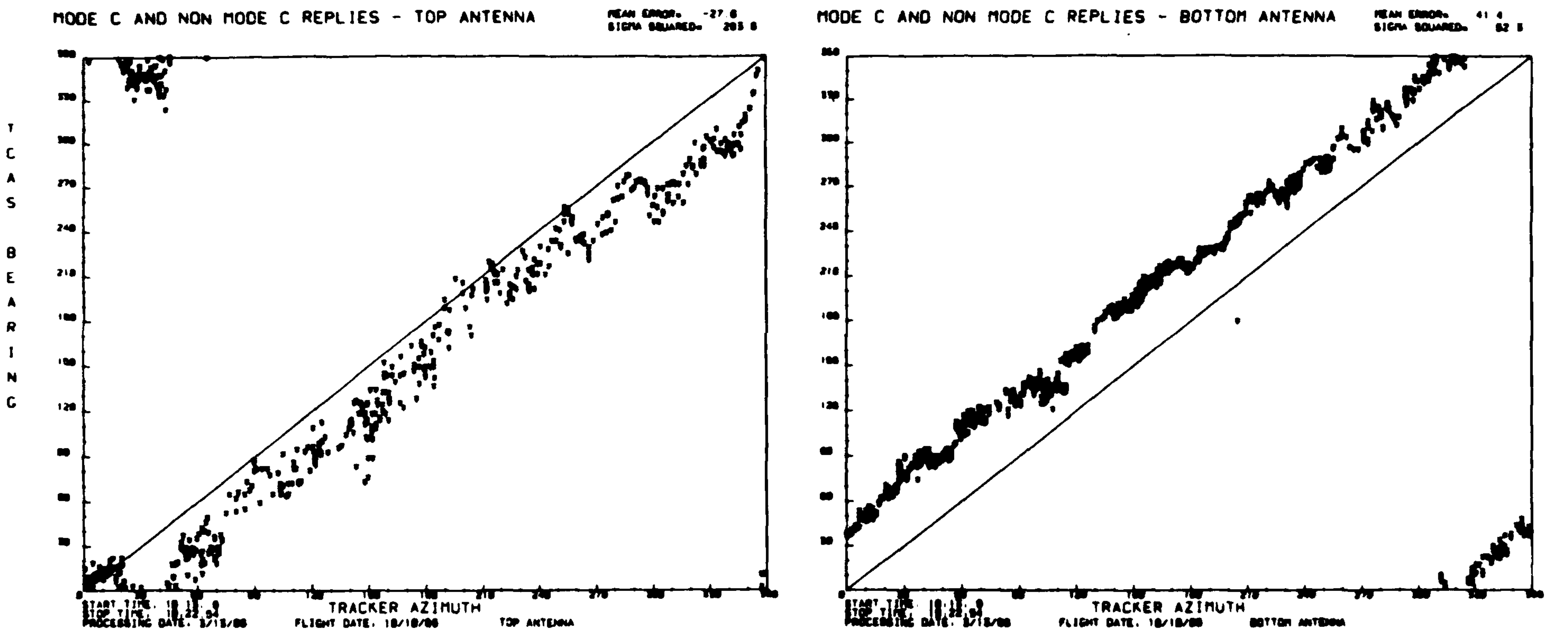


FIGURE A-4. TCAS BEARING VS TRACKER AZIMUTH, RUNS 7 AND 8 - INTRUDER 750 FEET BELOW TCAS

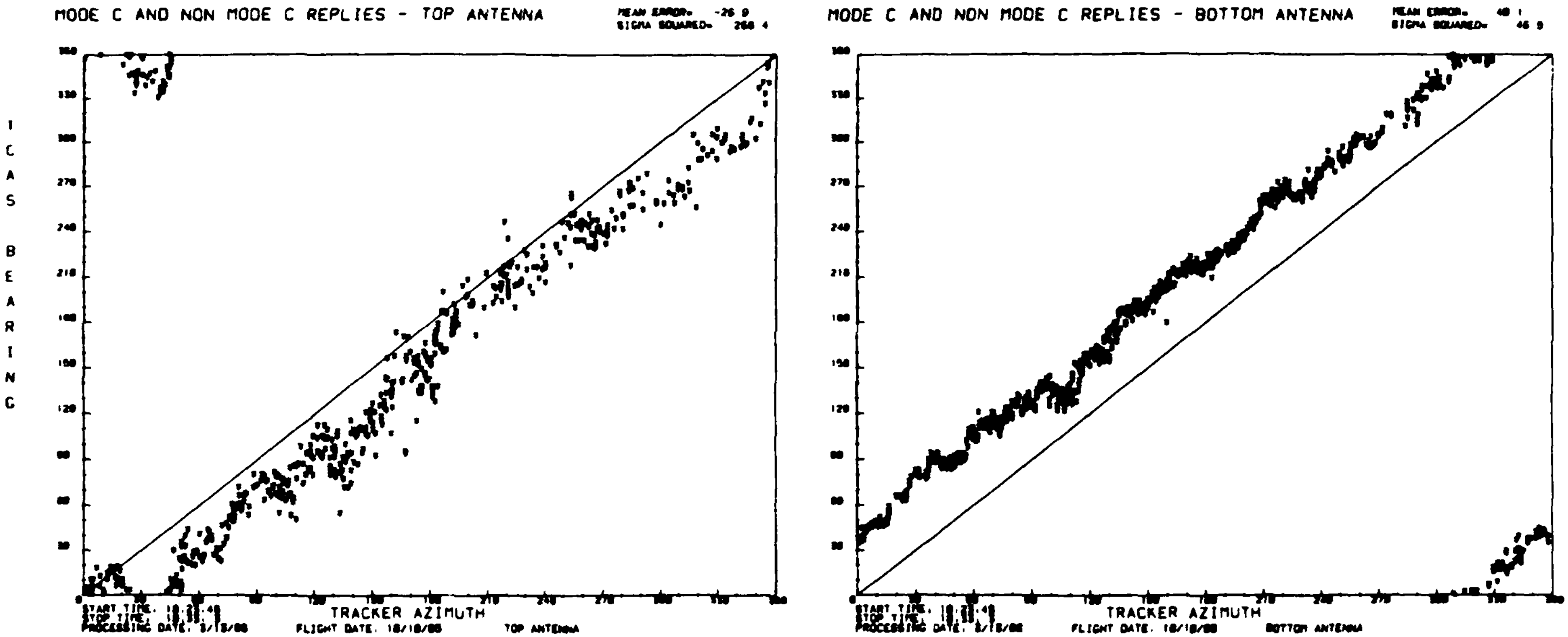


FIGURE A-5. TCAS BEARING VS TRACKER AZIMUTH, RUNS 9 AND 10 - INTRUDER 1000 FEET BELOW TCAS

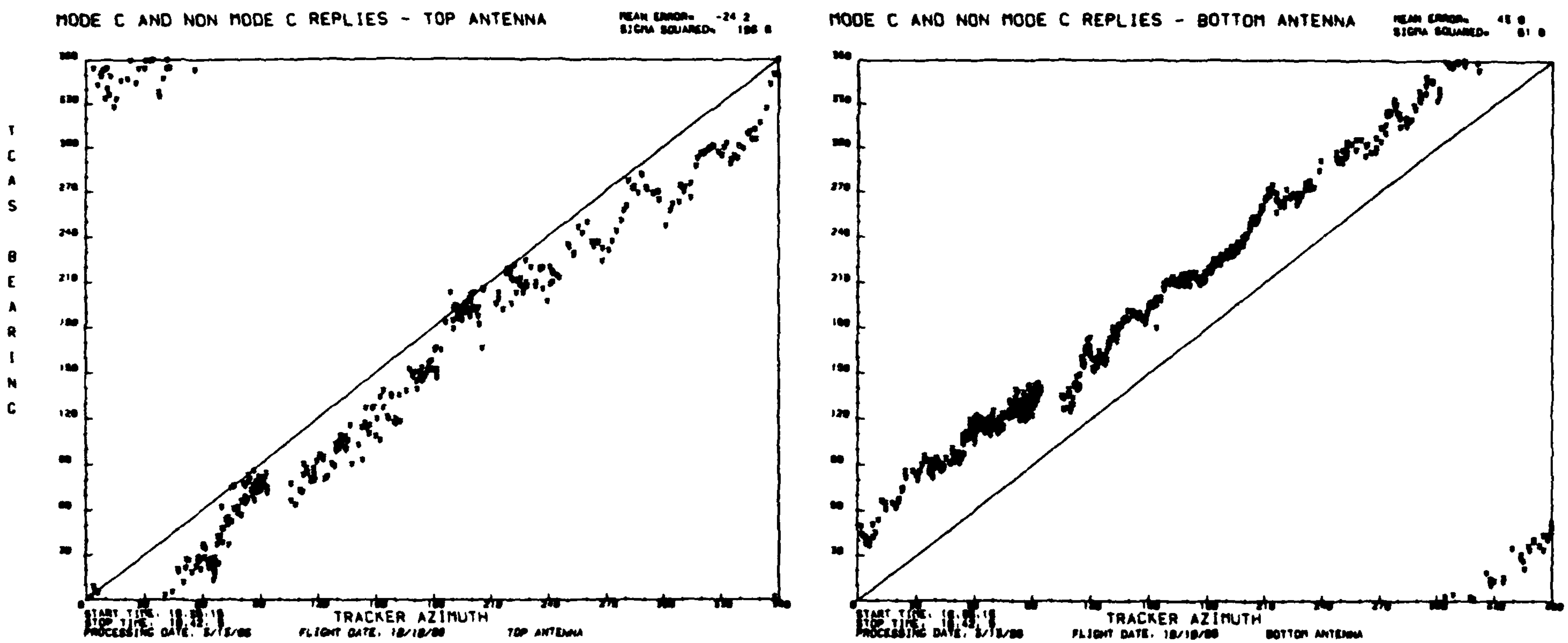


FIGURE A-6. TCAS BEARING VS TRACKER AZIMUTH, RUNS 11 AND 12 - INTRUDER 250 FEET ABOVE TCAS

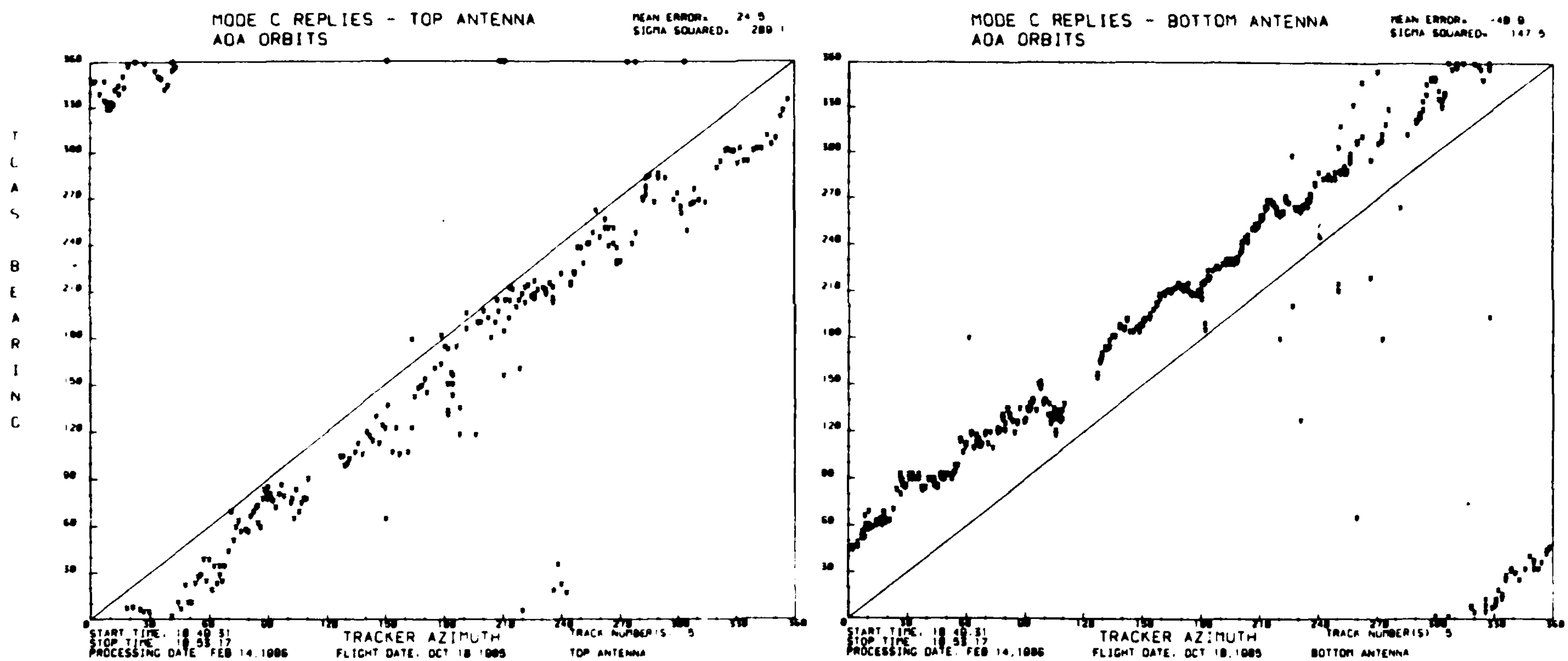


FIGURE A-7. TCAS BEARING VS TRACKER AZIMUTH, RUN 13 - INTRUDER 500 FEET ABOVE TCAS

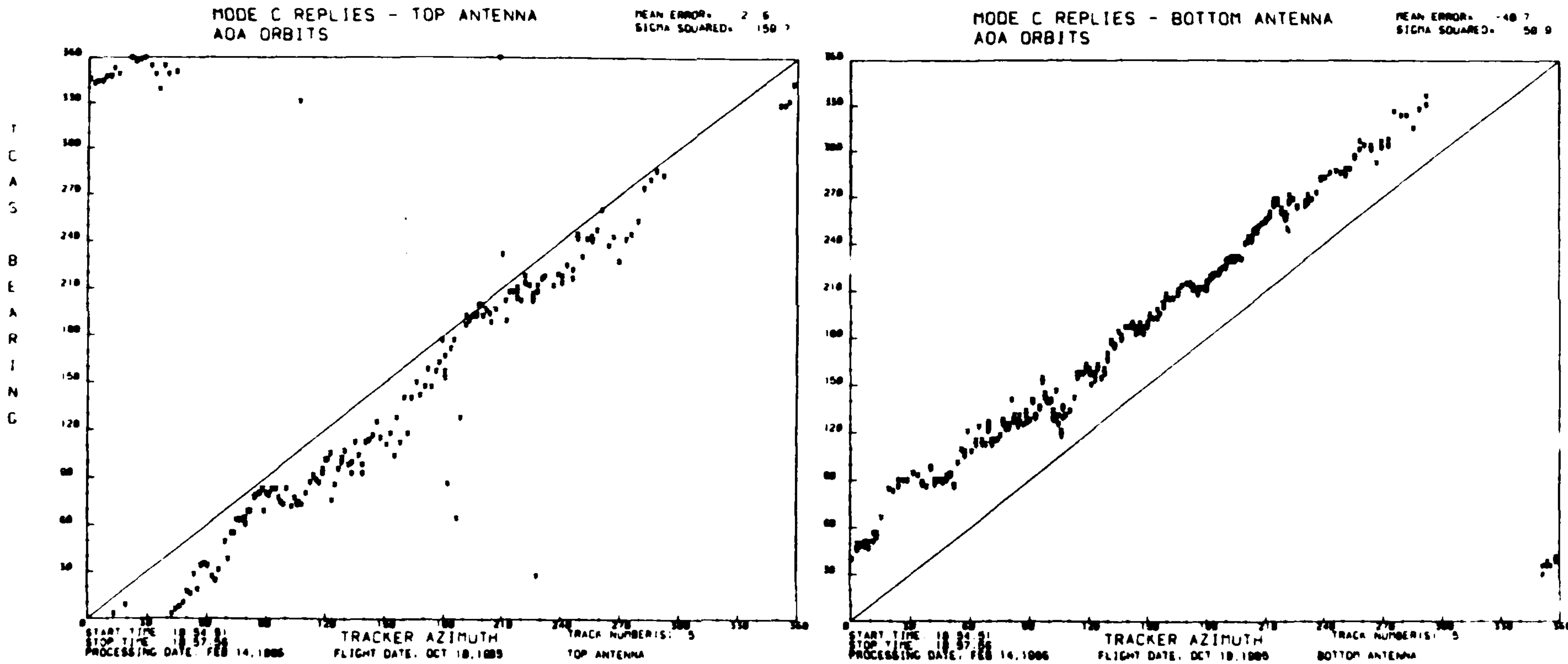


FIGURE A-8. TCAS BEARING VS TRACKER AZIMUTH, RUN 14 - INTRUDER 750 FEET ABOVE TCAS

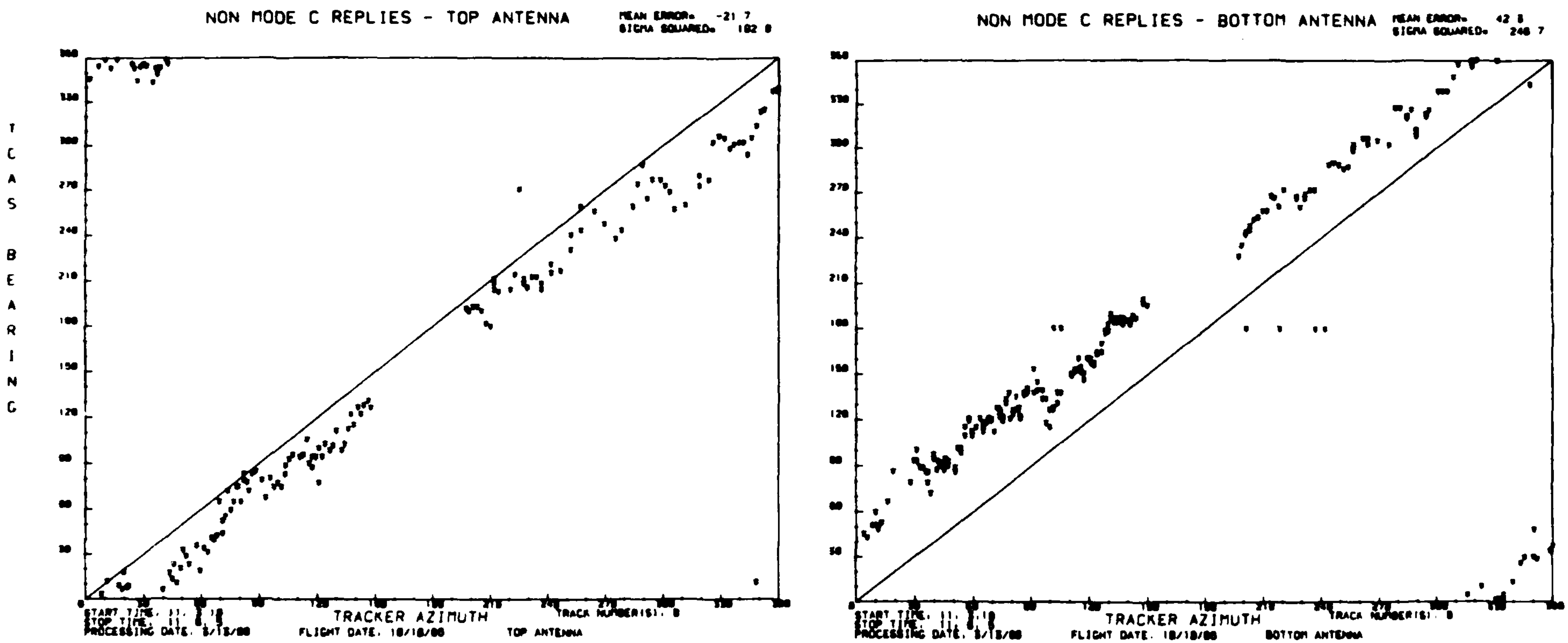


FIGURE A-9. TCAS BEARING VS TRACKER AZIMUTH, RUN 15 - INTRUDER 1000 FEET ABOVE TCAS

APPENDIX B

ANTENNA PATTERN PLOTS

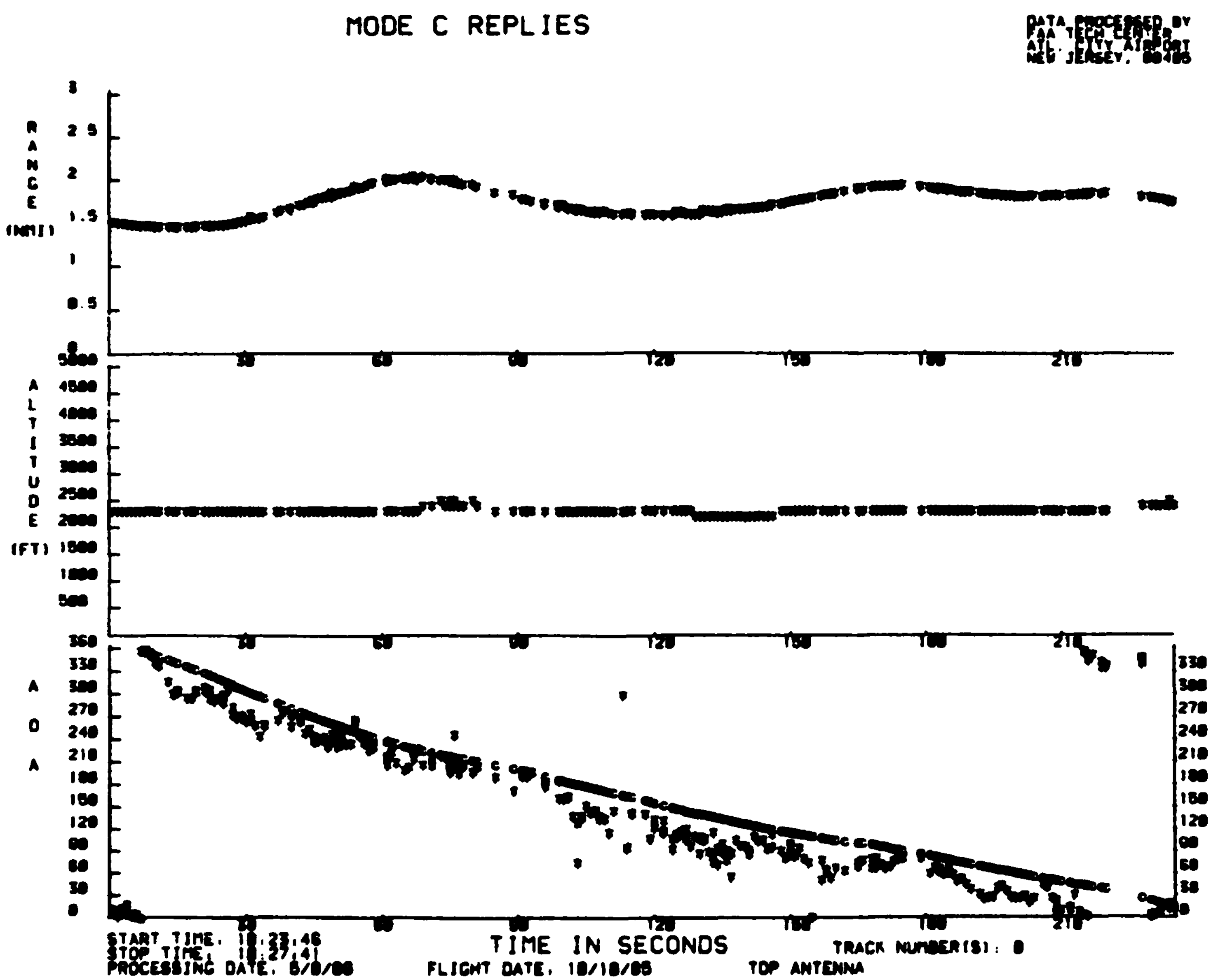


FIGURE B-1. RANGE, ALTITUDE, AND AOA OF INTRUDER AIRCRAFT, RUN 9 - INTRUDER 1000 FEET BELOW TCAS

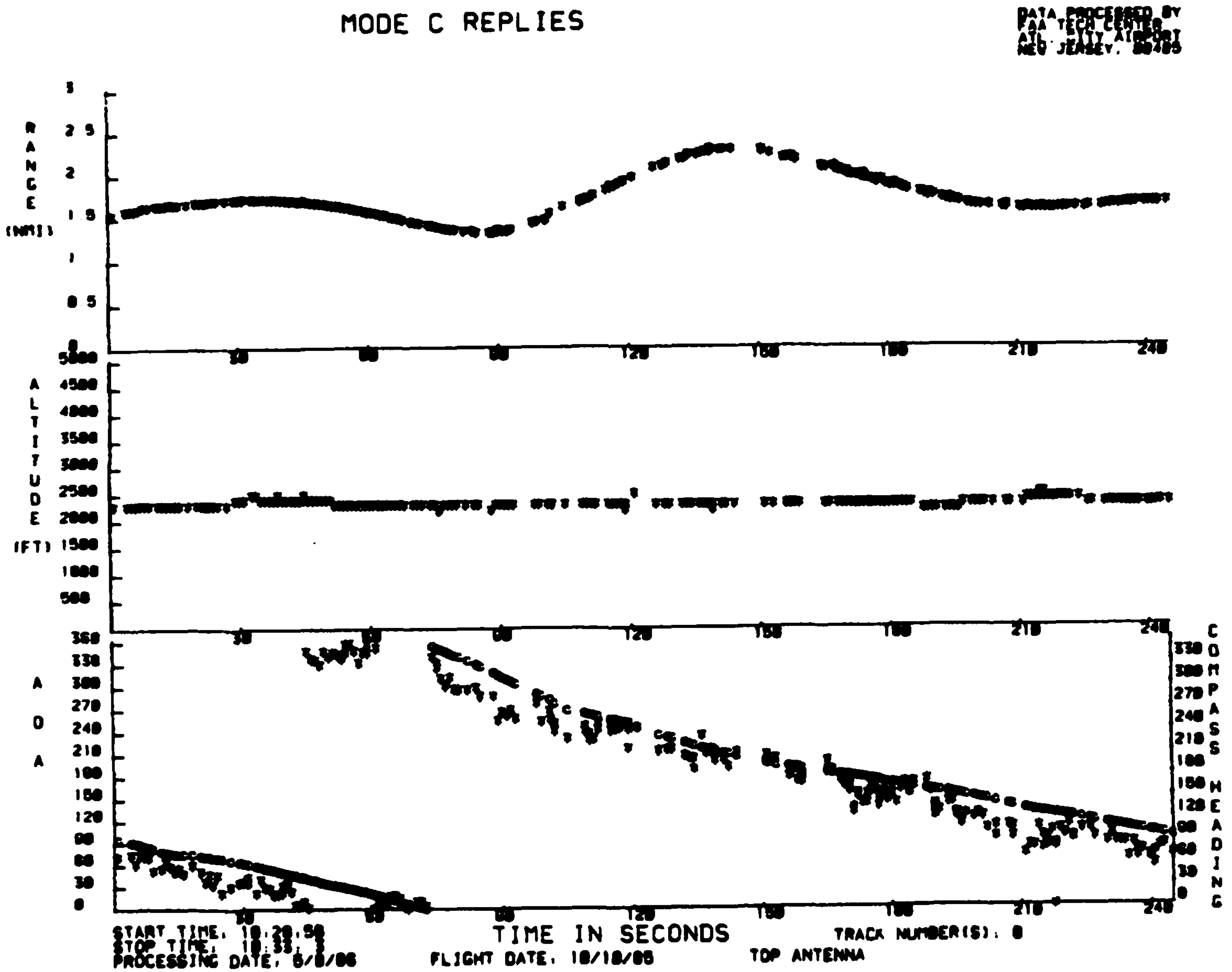


FIGURE B-2. RANGE, ALTITUDE, AND AOA OF INTRUDER AIRCRAFT, RUN 10 - INTRUDER 1000 FEET BELOW TCAS

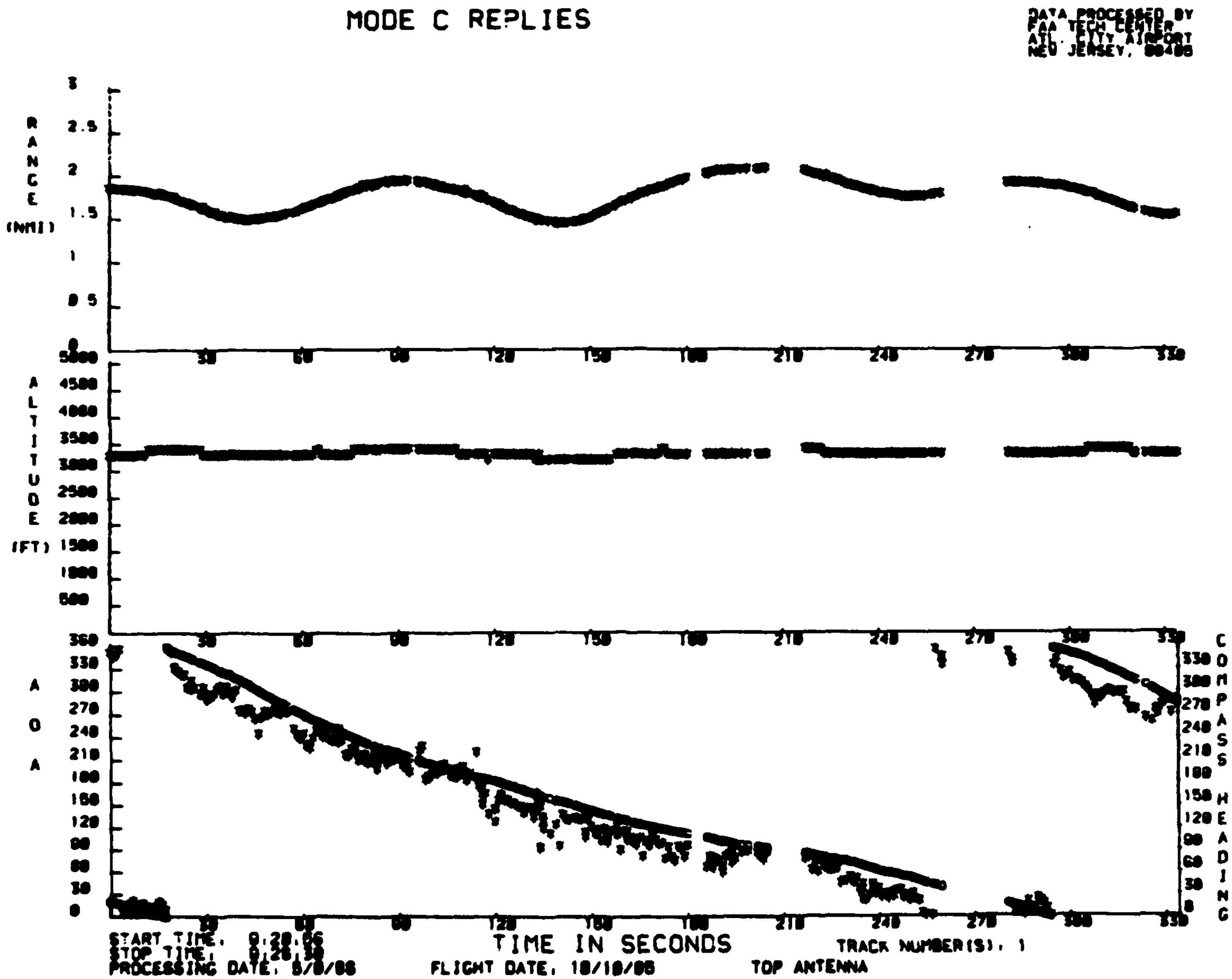


FIGURE B-3. RANGE, ALTITUDE, AND AOA OF INTRUDER AIRCRAFT, RUN 1 - INTRUDER COALTITUDE

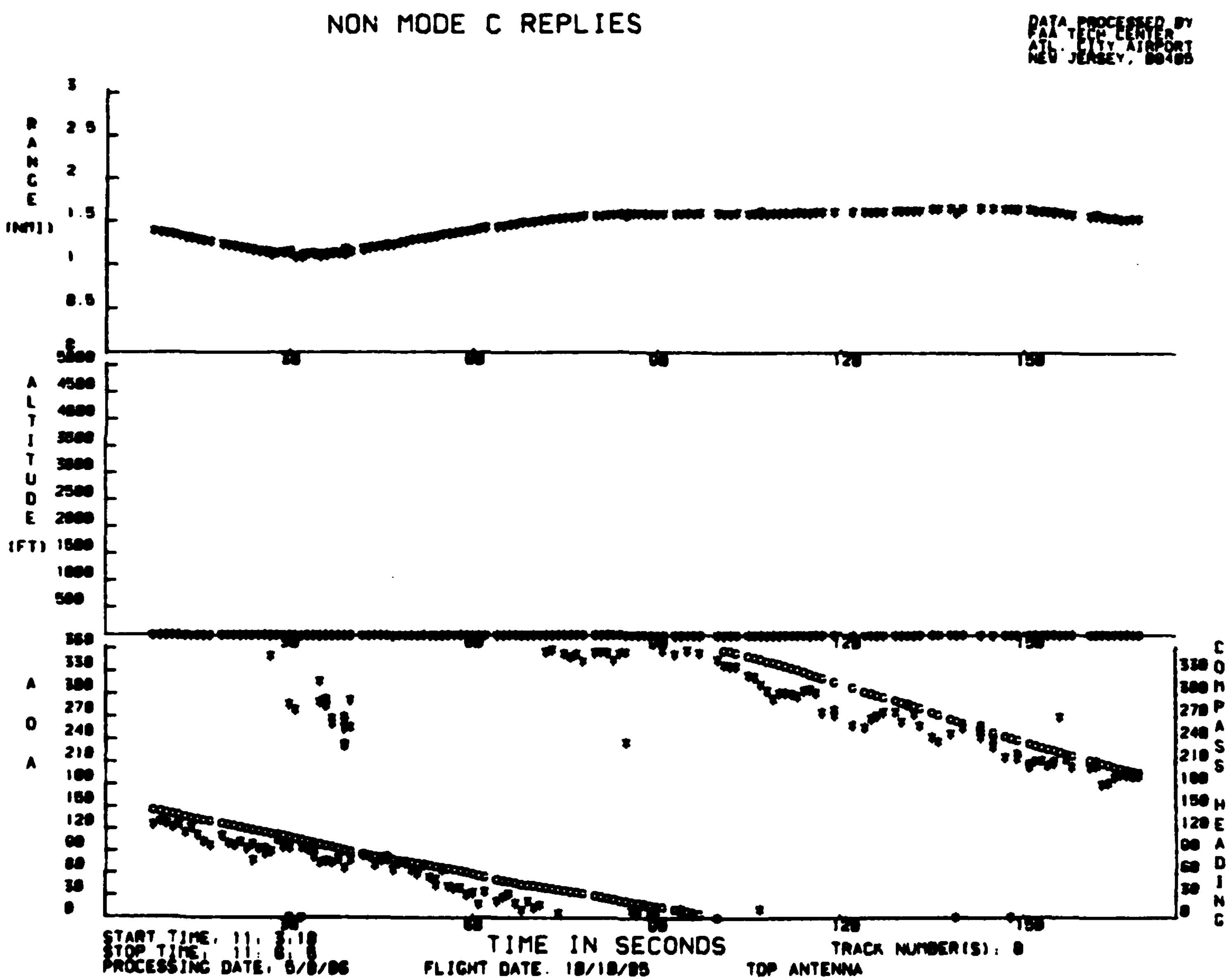


FIGURE B-4. RANGE, ALTITUDE, AND AOA OF INTRUDER AIRCRAFT, RUN 15 - INTRUDER 1000 FEET ABOVE TCAS

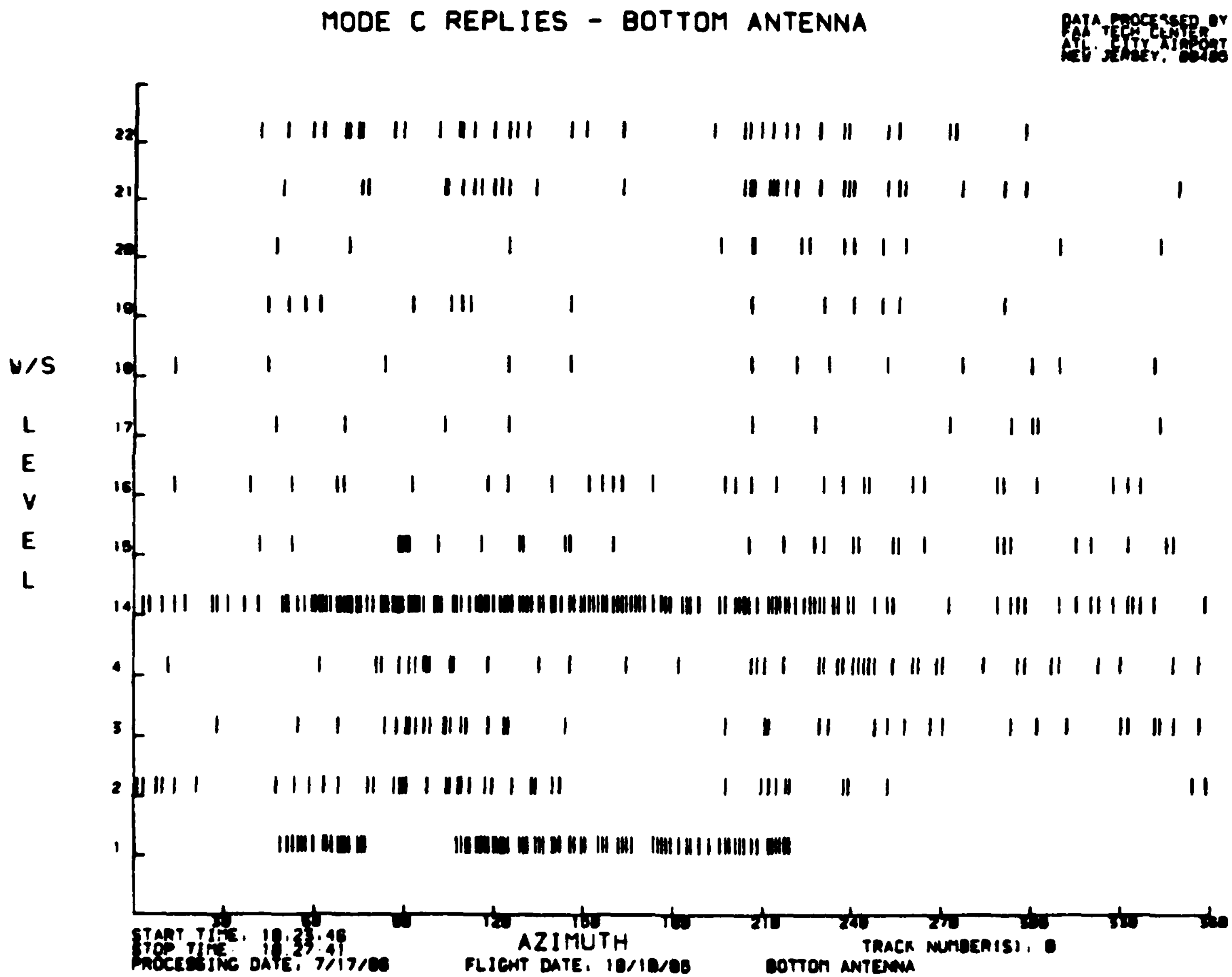


FIGURE B-5. RECEIVED REPLIES VS WHISPER SHOUT LEVEL, RUN 9 (SHEET 1 of 2)

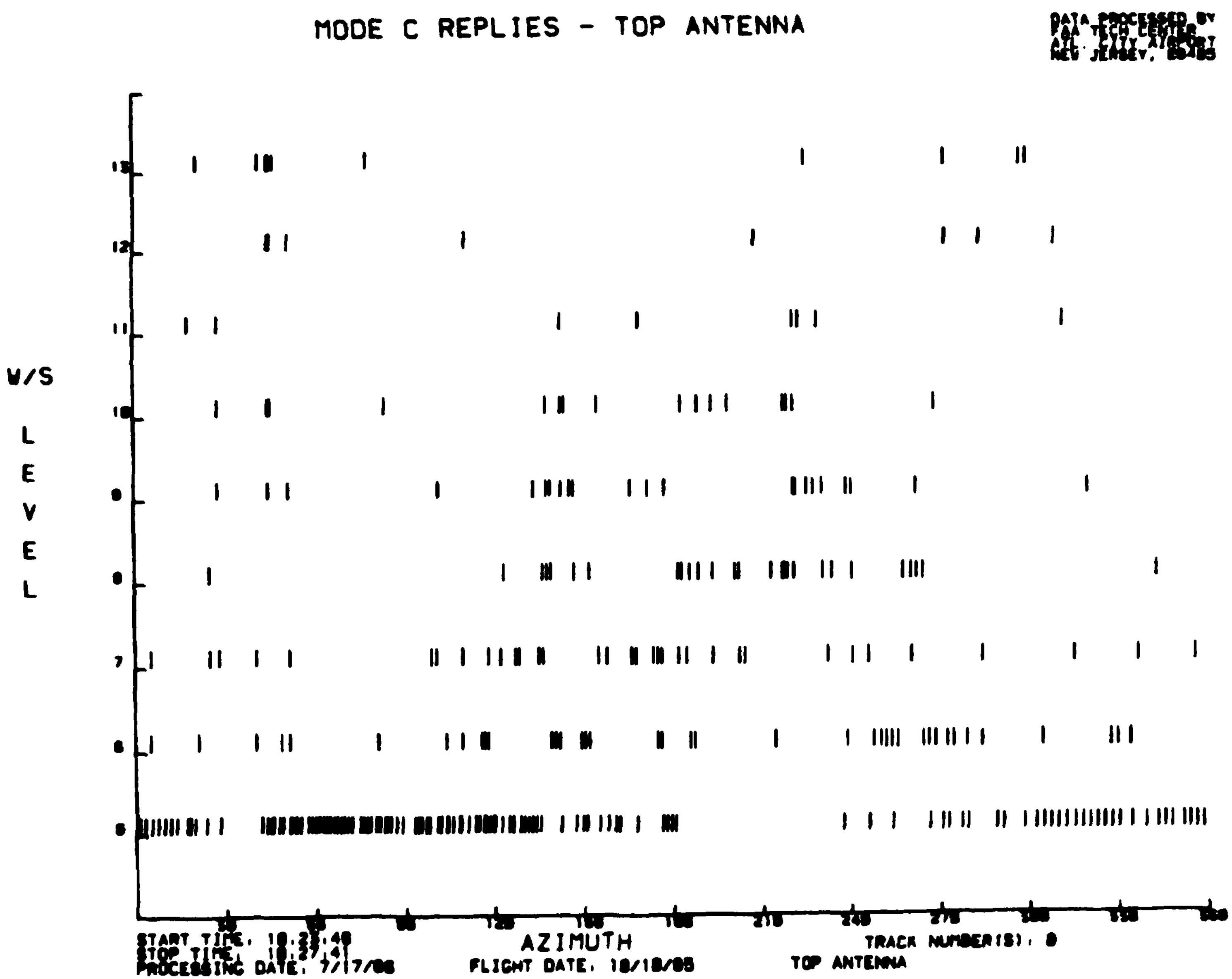


FIGURE B-5. RECEIVED REPLIES VS WHISPER SHOUT LEVEL, RUN 9 (SHEET 2 of 2)

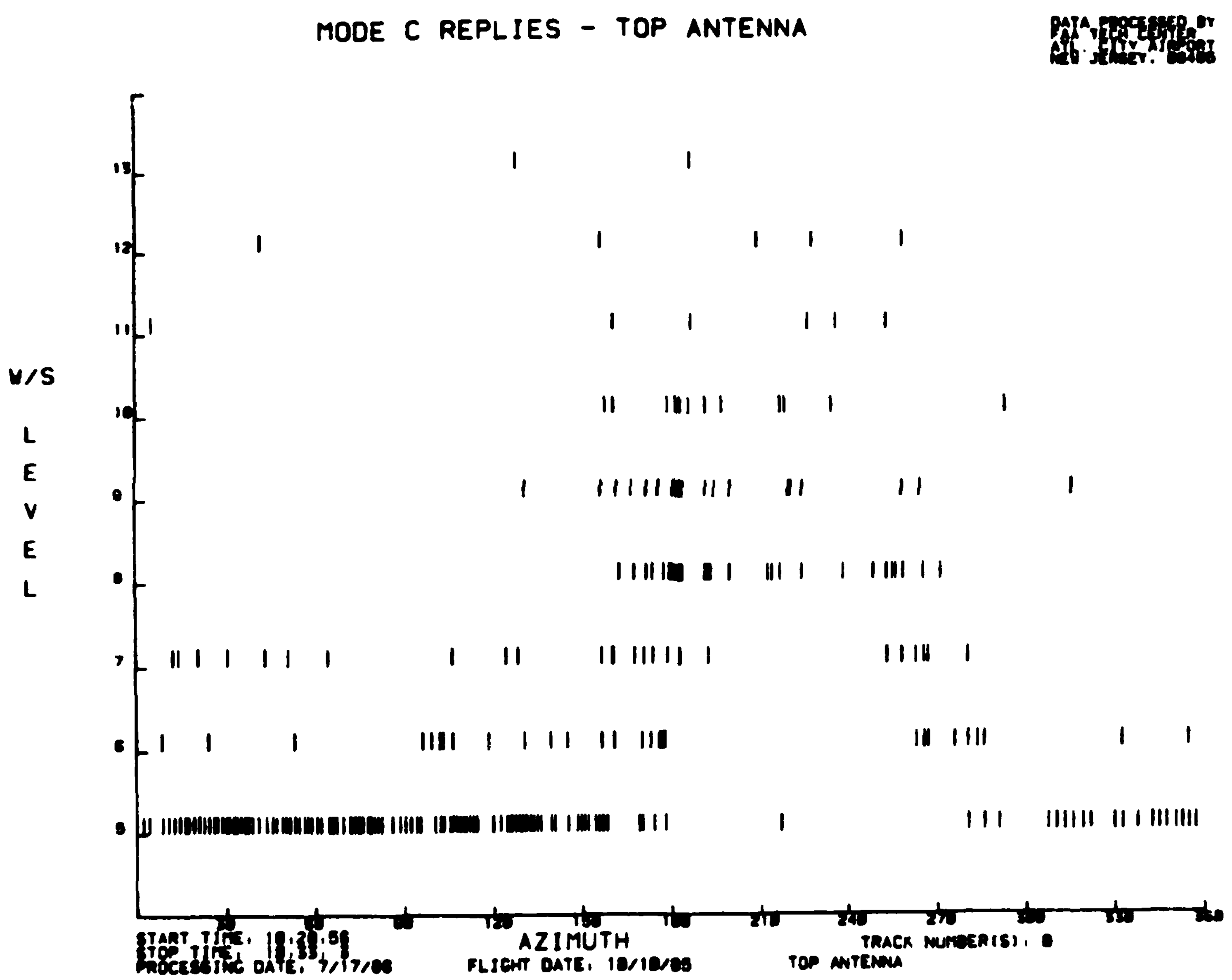


FIGURE B-6. RECEIVED REPLIES VS WHISPER SHOUT LEVEL, RUN 10 (SHEET 1 of 2)

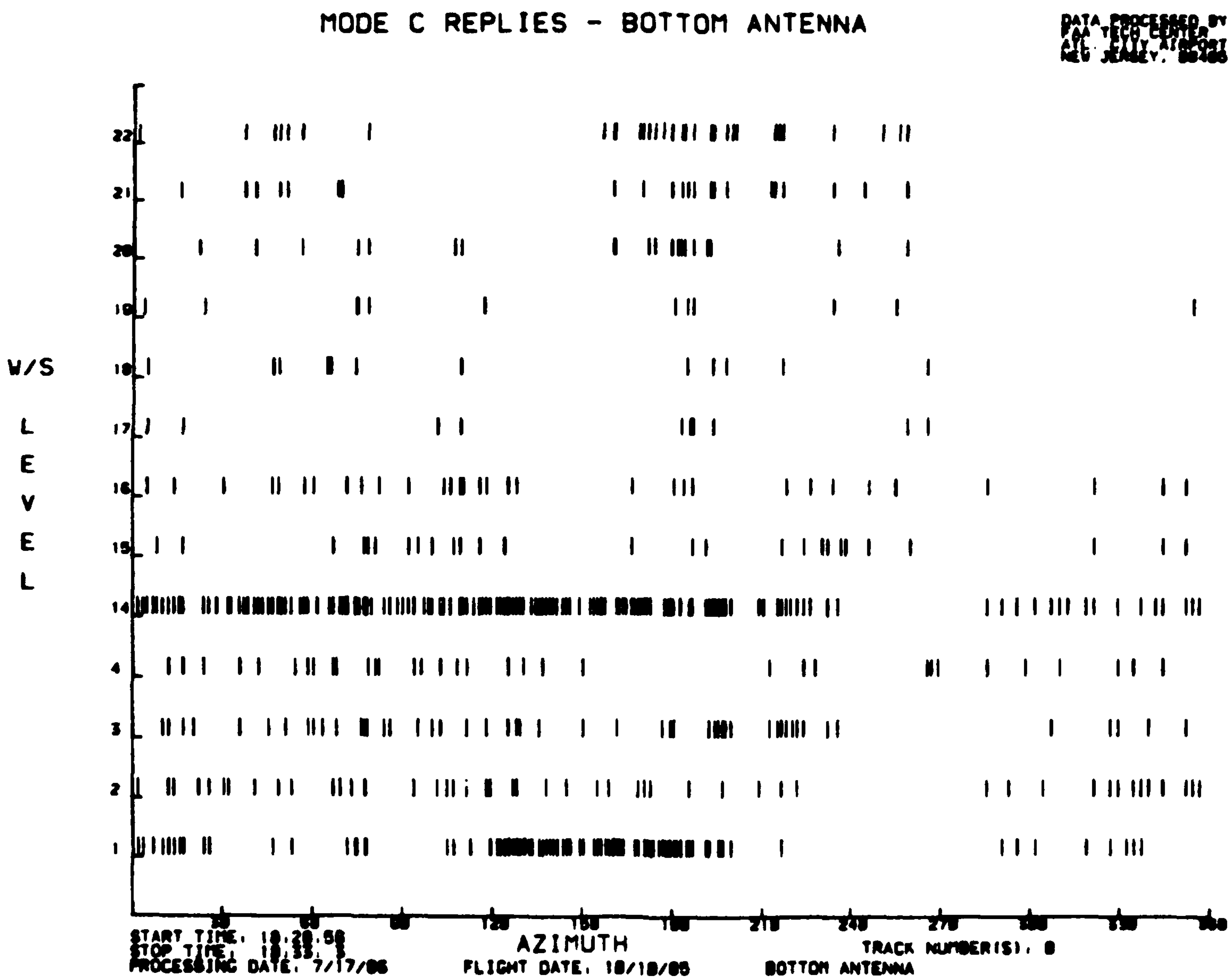


FIGURE B-6. RECEIVED REPLIES VS WHISPER SHOUT LEVEL, RUN 10 (SHEET 2 of 2)

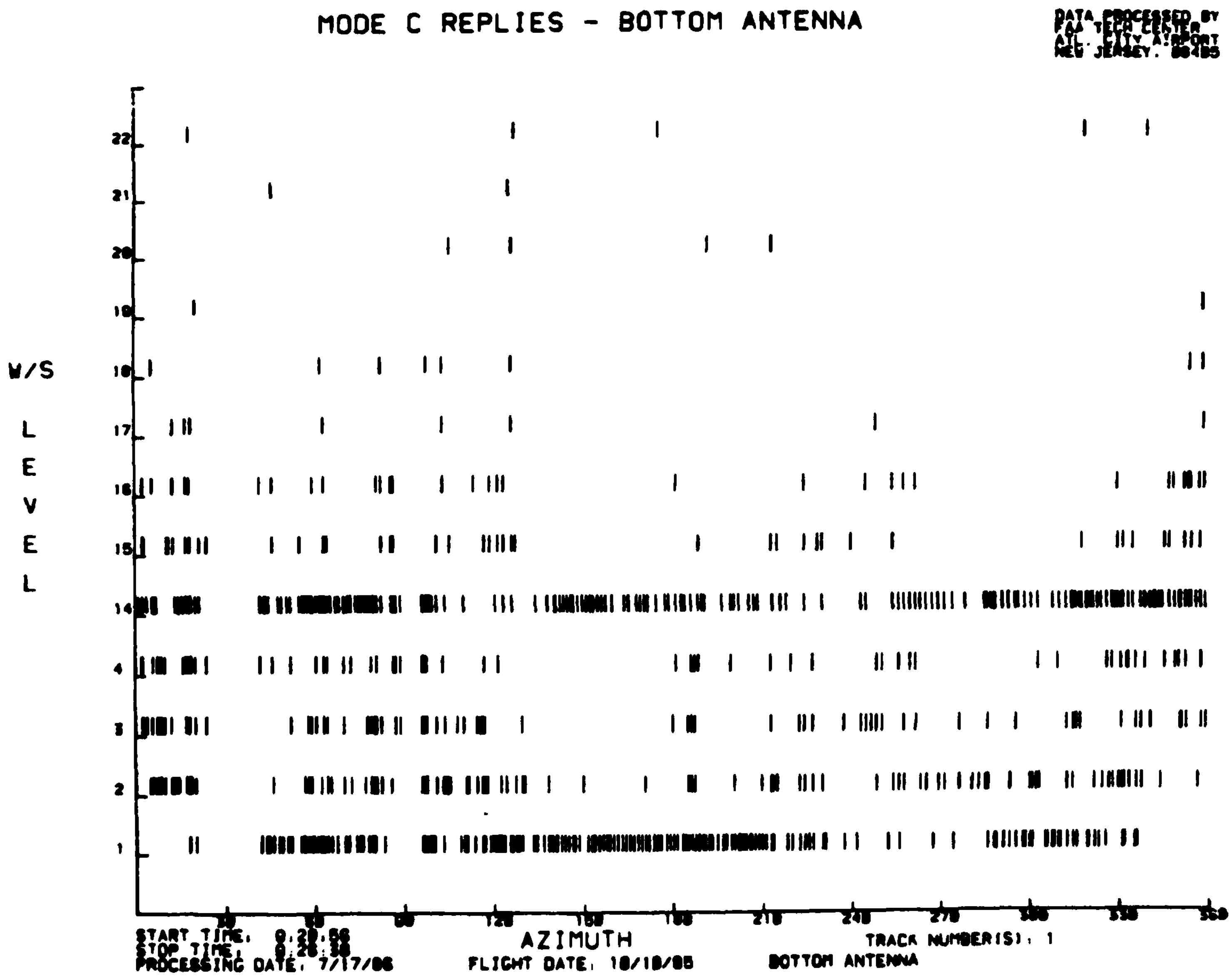


FIGURE B-7. RECEIVED REPLIES VS WHISPER SHOUT LEVEL, RUN 1 (SHEET 1 of 2)

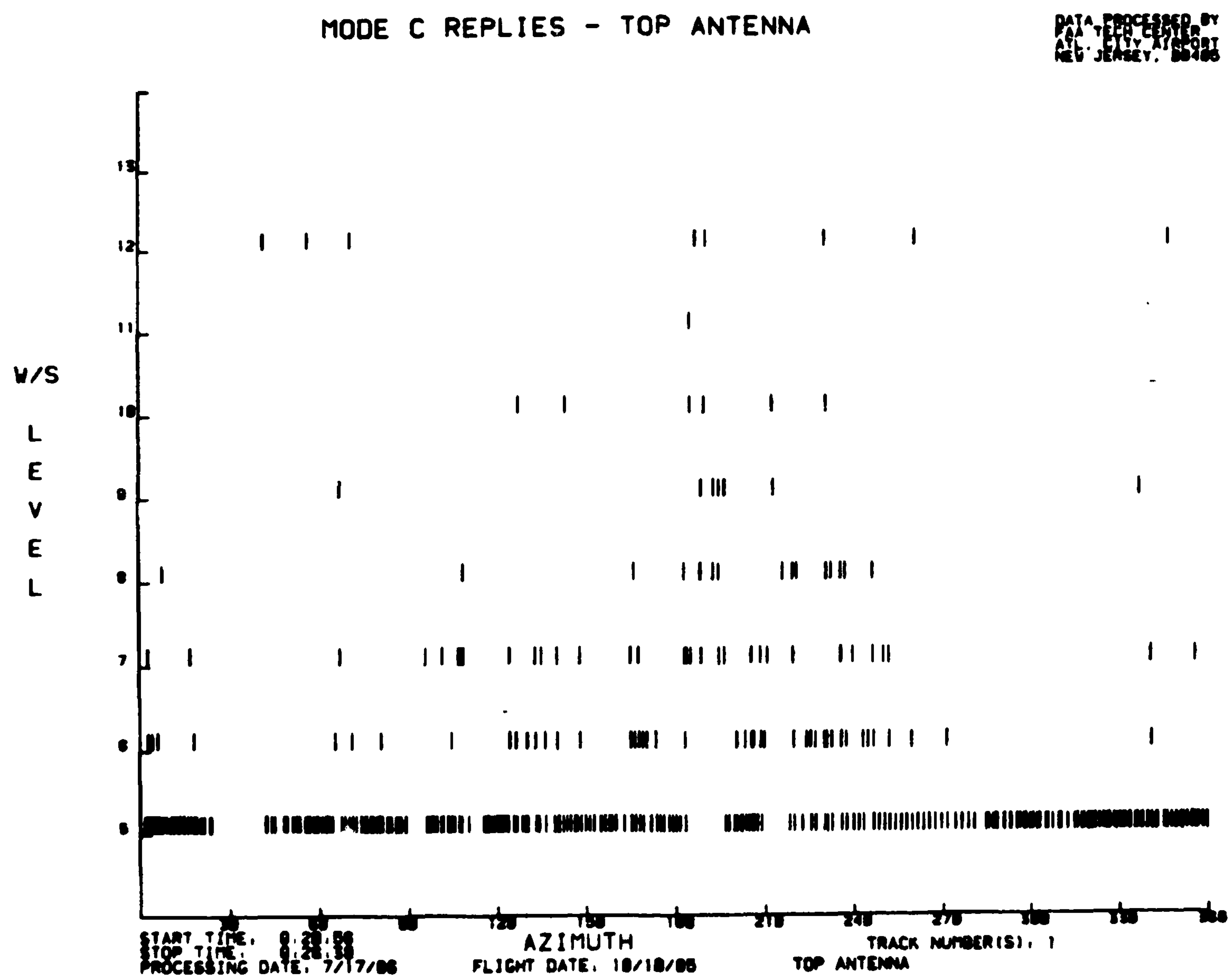


FIGURE B-7. RECIEVED REPLIES VS WHISPER SHOUT LEVEL, RUN 1 (SHEET 2 of 2)

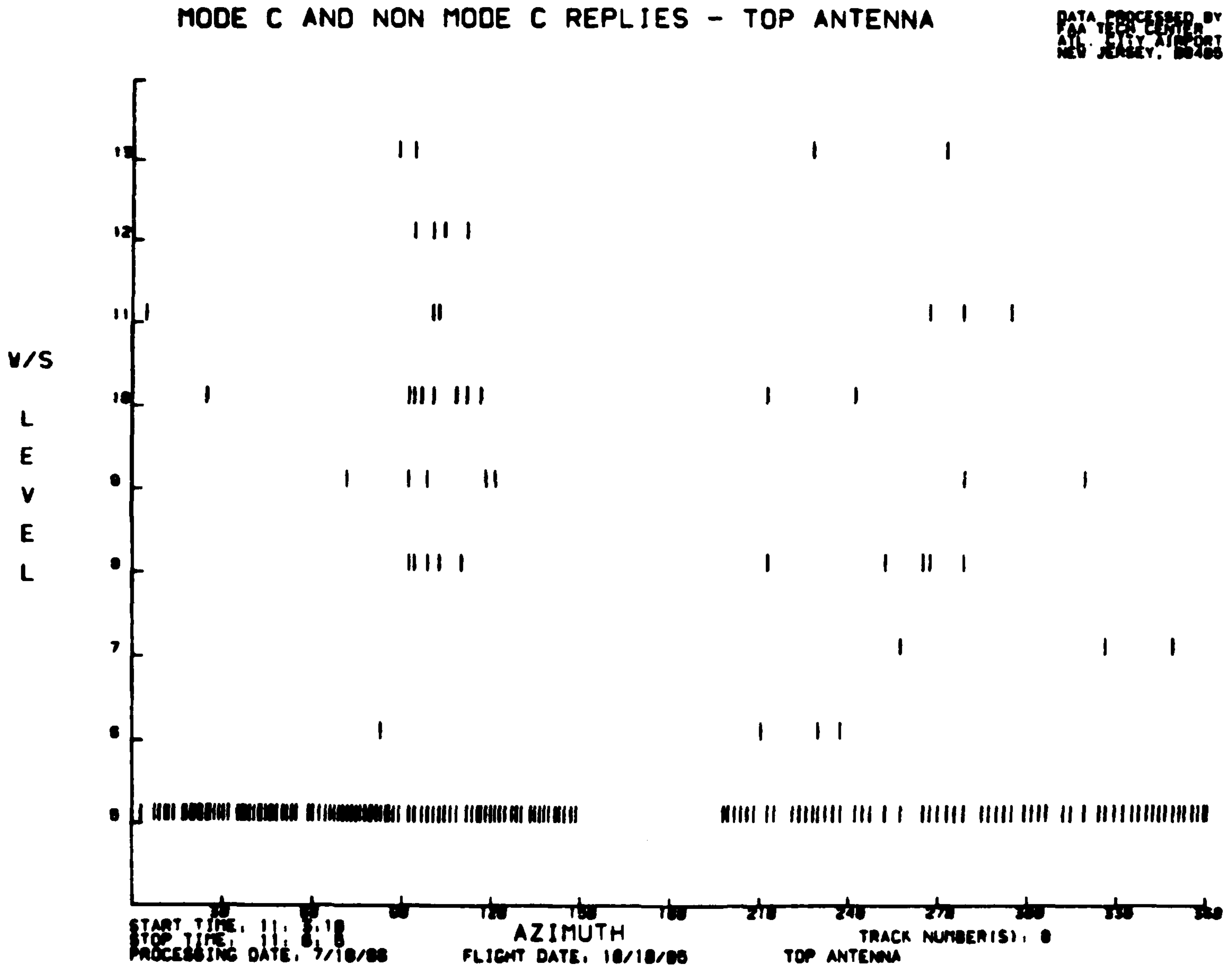


FIGURE B-8. RECEIVED REPLIES VS WHISPER SHOUT LEVEL, RUN 15 (SHEET 1 of 2)

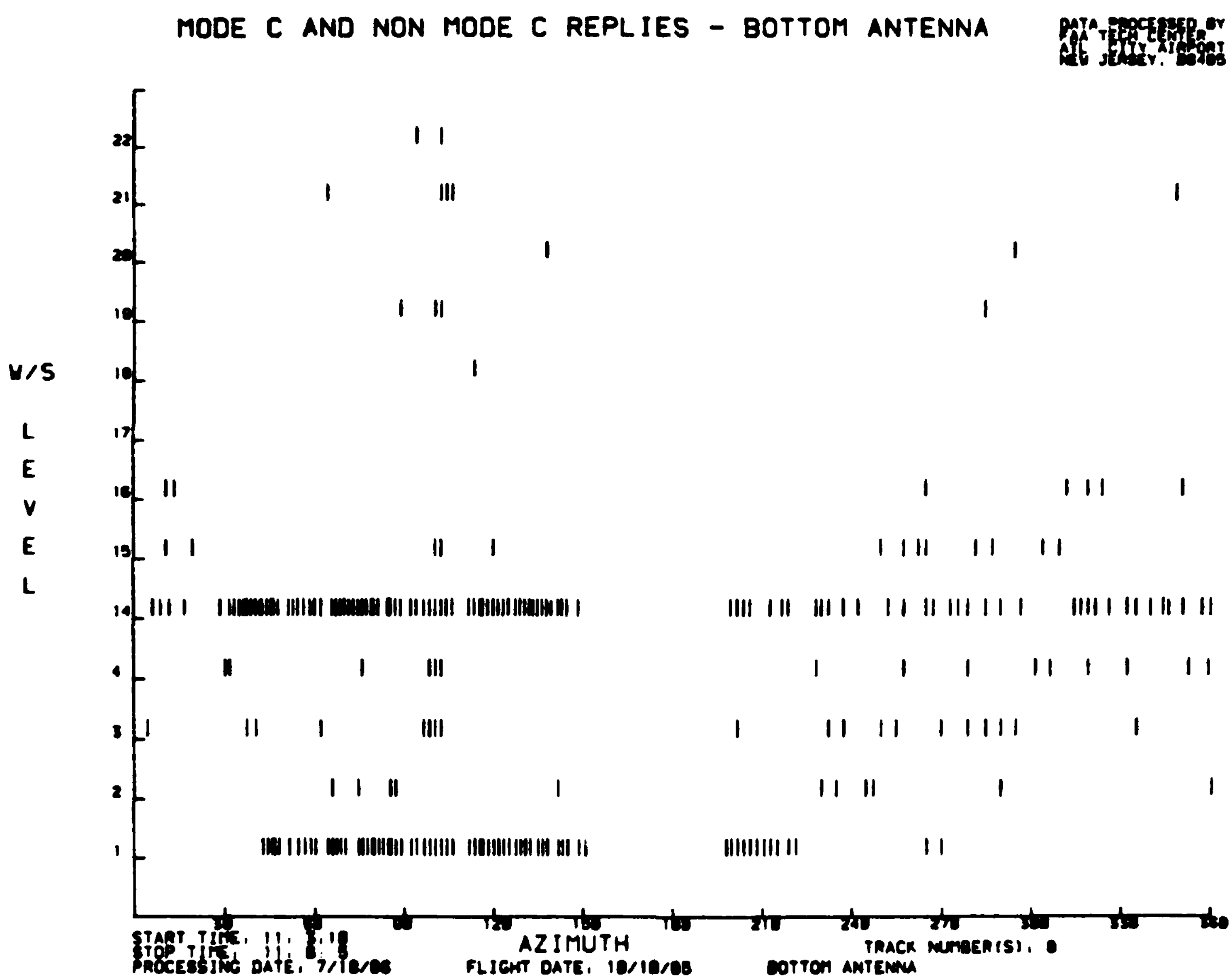
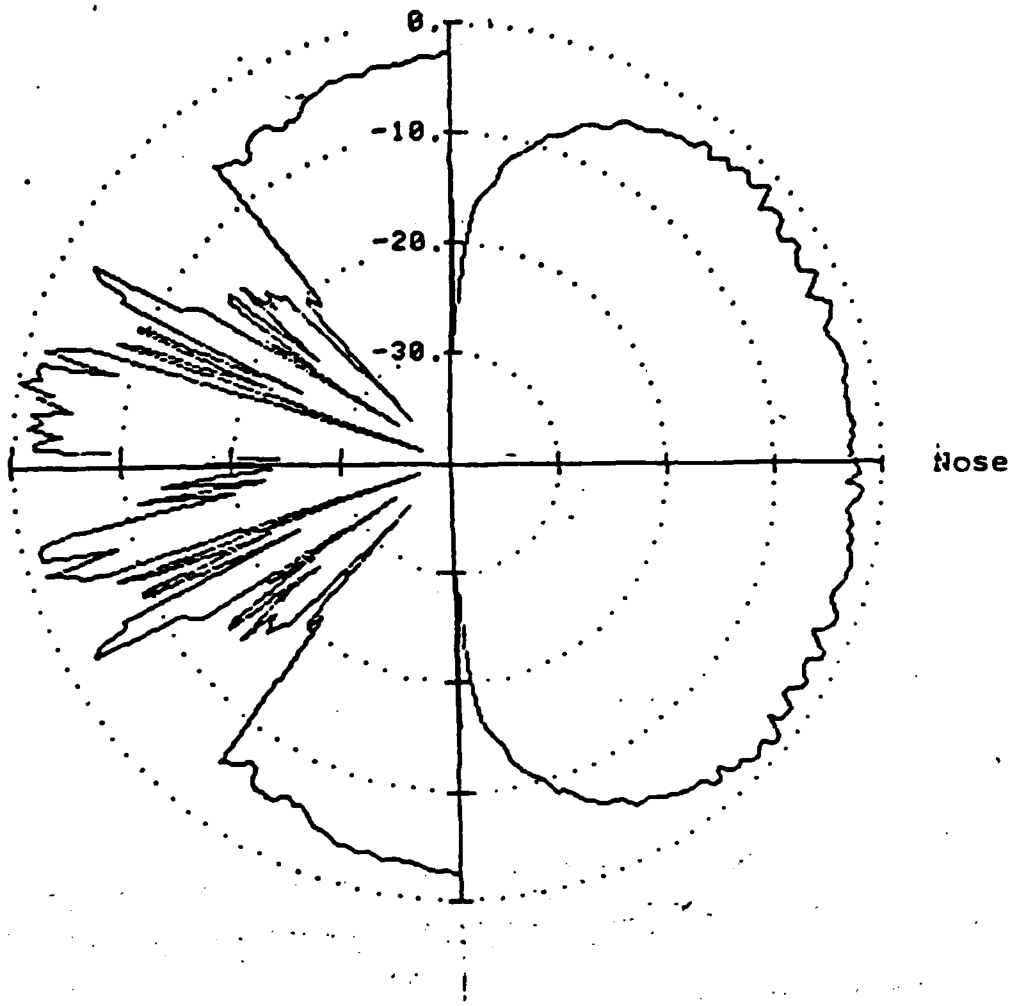


FIGURE B-8. RECEIVED REPLIES VS WHISPER SHOUT LEVEL, RUN 15 (SHEET 2 of 2)

APPENDIX C

5 GHz ANTENNA PATTERNS FOR SIKORSKY S-76

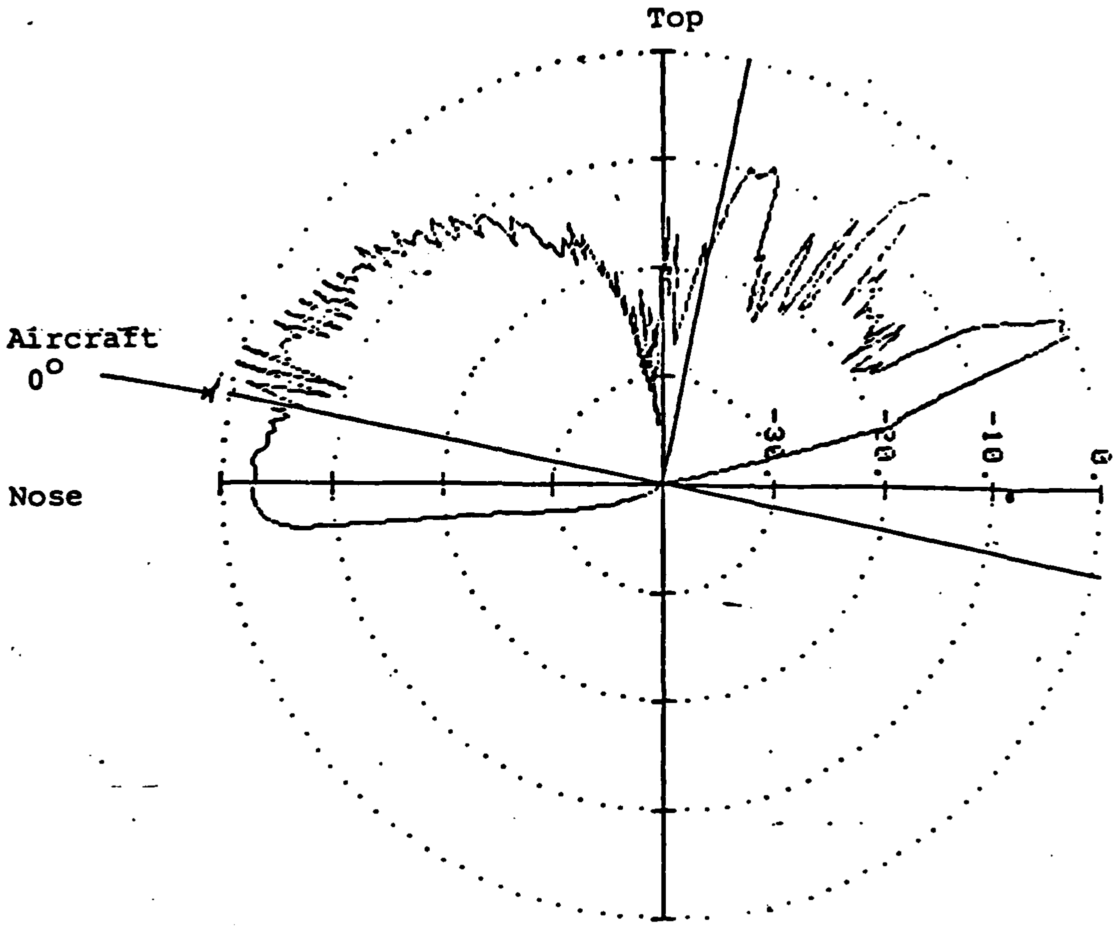


Azimuth Pattern - Antenna on Aircraft Nose
Elevation Angle Zero Degree

Station No. 42

Sikorsky S-76

FIGURE C-1. AZIMUTH PATTERN - ANTENNA ON AIRCRAFT NOSE



Elevation Pattern of Nose Antenna, Sikorsky S-76
Ground Plane Extends to Radome Mounting Edge/Bulkhead
Ground Plane 10.5" x 7"

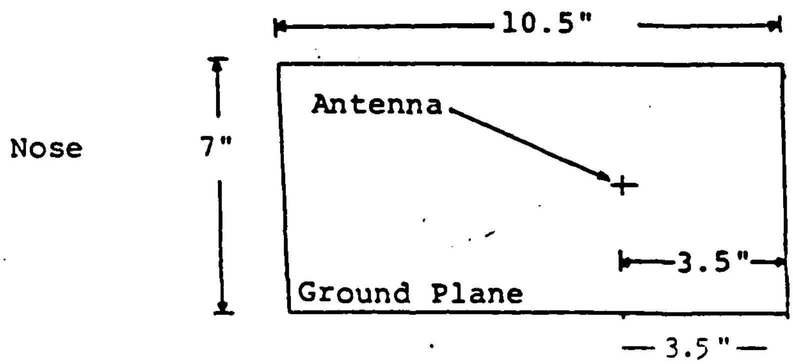
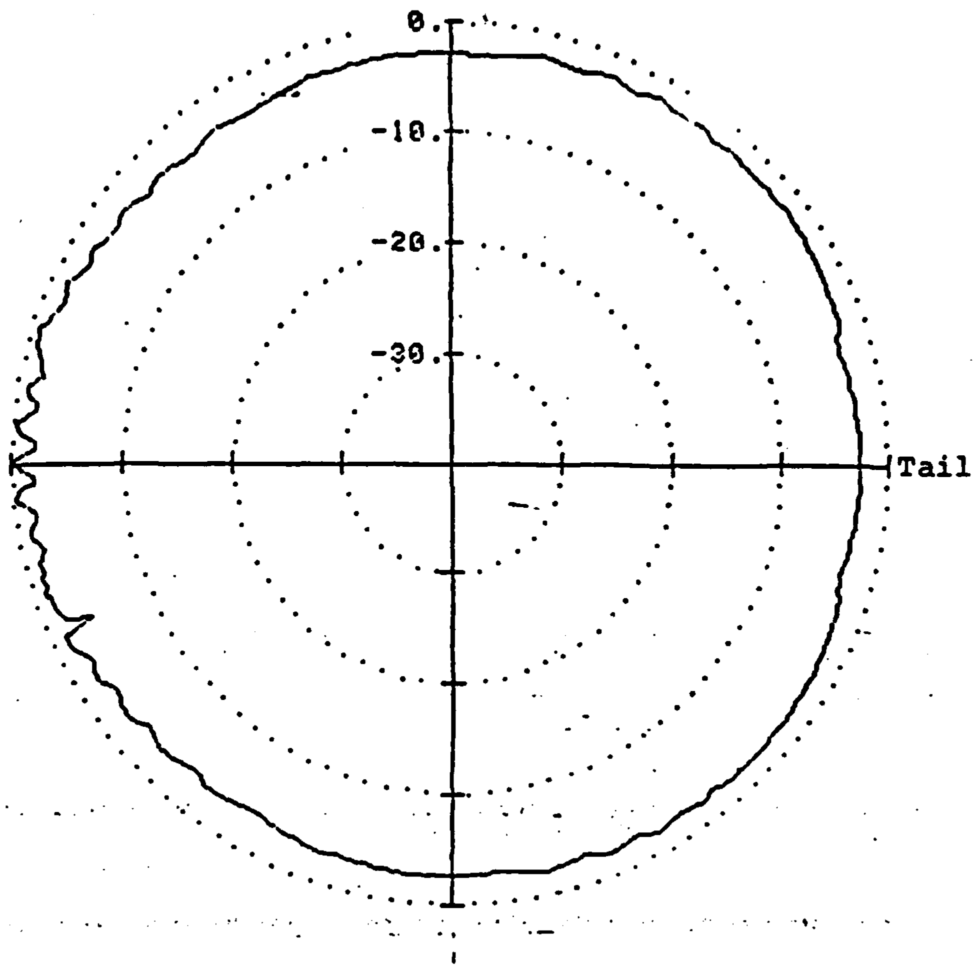


FIGURE C-2. ELEVATION PATTERN - ANTENNA ON AIRCRAFT NOSE



Azimuth Pattern

(Antenna Station 316.3)

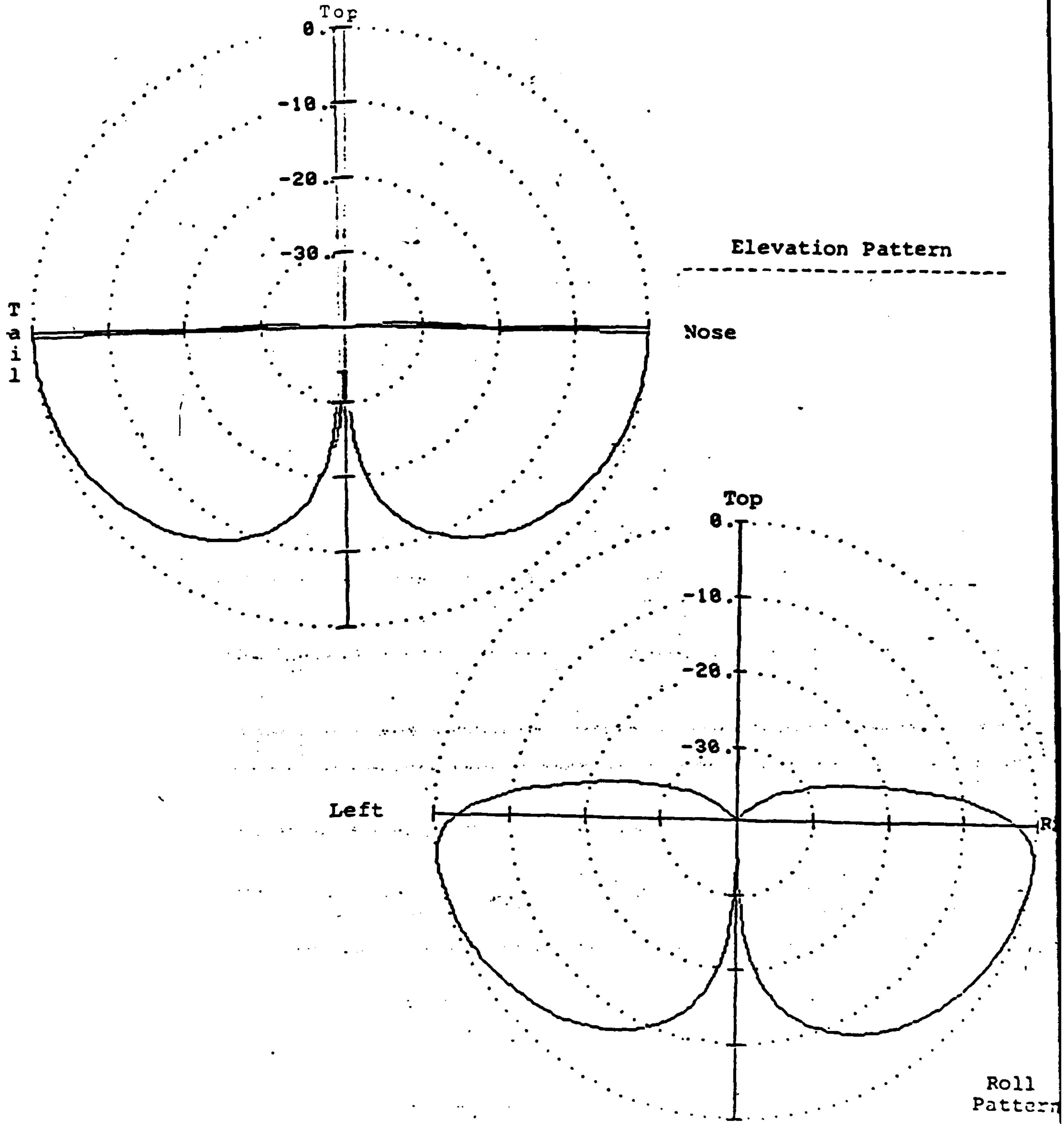
Lower Rear Fuselage

Landing Gear Deployed

Elevation Angle Zero Degree

Sikorsky S-76

FIGURE C-3. AZIMUTH PATTERN - ANTENNA ON LOWER REAR FUSELAGE



Elevation & Roll Patterns, (Station 316.3),
Lower Rear Fuselage, Landing Gear Depolyed
Elevation Angle Zero Degree

Sikorsky S-76

Mounted Receive Antenna Angle 10°

FIGURE C-4. ELEVATION PATTERN - ANTENNA ON LOWER REAR FUSELAGE

END

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